FOREST SOILS

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FOREST SOILS

THEIR PROPERTIES AND RELATION TO SILVICULTURE

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To
Larissa Wilde
my lodestar in the voyage across the
stormy sea of life

Preface

During the decade following World War II the business of timber production in the United States and elsewhere underwent drastic changes in many of its aspects—land ownership, conditions of amortization, marketing and utilization of forest products, approach toward management, and technique of silvicultural operations. These changes have transformed many foresters from naturalists into chemically and mechanically minded technicians as well as business executives. Specialists in forest soils likewise have had to face new problems and responsibilities.

With these innovations in mind, this book was written to meet the requirements of students of forestry and soils, and to be of service to specialists engaged in utilization of forest lands.

An attempt was made to take full account of three recent developments in forest practice: the large-scale use of chemicals in the production of nursery stock and in other phases of silviculture; insufficient increment of stands and plantations on soils of depleted fertility; and erratic results obtained with partial cuttings conducted according to the empirical rules of silvicultural "art." Therefore, particular attention was given to the following tasks that are of cardinal importance in a planned timber production:

(a) maintenance of nursery soil fertility and the correction of toxic effects produced by soluble salts and various eradicants;

(b) survey of forest lands and selection of planting sites suitable to different tree species;

(c) diagnosis of adverse conditions responsible for poor growth of trees, and amelioration of soils of low productivity by application of fertilizers and by other means;

(d) detection and evaluation of changes produced in the composition of the soil by different silvicultural treatments;

(e) correlation of forest management with the productive potential of forest lands.

The successful handling of these problems requires not only a grasp of technicalities, but also a knowledge of basic relationships, a knowledge which allows the analytical information to be synthesized into a conclusion of practical significance.

To accommodate the teaching schedule, the course may be condensed into one semester or extended over a greater period, possibly including a summer session. On the other hand, fragmentation of the subject into the required "basic" course and an elective "advanced" course would be just as inadequate as allowing a medical student to elect only part of the required curriculum. No physician could succeed in his practice equipped with the knowledge of the skeleton and muscles alone, and no forester can profit from a conglomerate of abstract pedological classifications and agronomical procedures divorced from silviculture. Utmost effort, therefore, was made in this text to interpret available information on soils in terms of important features of forest stands—their composition, rate of growth, quality of forest products, capacity for natural regeneration, and stability against adverse climatic and biotic factors.

The comprehension of soil's influence on these all-important aspects of forest growth can be best transmitted to the students by devoting a good share of the laboratory hours to actual examination of soils and forest cover. Only through an extensive use of the outdoor periods can the students learn to see the entire forest beyond the individual trees and to visualize the broad horizons of an improved tree growth and increased financial return beyond the narrow soil horizons. This field work will help students to grasp that their study is not solely concerned with the properties of lifeless samples torn from the body of the soil by a spade or other implement. The ultimate objective is the understanding of the needs of living organisms which provide us with wood and numerous intangible benefits and which often suffer from thirst, hunger, and suffocation.

To Professor Emil Truog I owe a debt of gratitude for his quarter-century-long guidance in matters concerning soil fertility and plant nutrition. My deep appreciation is extended to Professor G. K. Voigt of Yale University and Professor Howard Loewenstein of the State University of New York for their untiring help in the field, in the laboratory, and at the writing desk. In the preparation of certain parts of the manuscript I have had the benefit of advice and criticisms from Drs. I. C. M. Place (silviculture), F. D. Hole (soil survey), D. P. White (nutrition and use of fertilizers), C. B. Tanner (soil physics), R. B. Corey and M. L. Jackson (soil chemistry), and C. B. Davey (soil biology). Messrs. W. H. Brener and Leif Steiro of the Wisconsin Conservation Department, Miss Margaret Stitgen, secretary of the Soils Department, University of Wisconsin, and my graduate students contributed in various ways to the completion of this text. To all of these I express my cordial thanks.

I gratefully acknowledge the contributions of several of my European colleagues, who generously shared their ideas and experiences with me. This is particularly true of Dr. Ph. Duchaufour of the École des Eaux et Forêts of France, Professor R. Ganssen of Freiburg University, Professor Franz Hartmann of the Vienna College of Agriculture, Dr. G. V. Jacks of the Rothamsted Experiment Station, Dr. F. Mancini of the Florence School of Agriculture, Dr. F. Richard of the Zurich Forest Experiment Station, and Professor W. Wittich of the University of Göttingen. I am also grateful to many never-to-be-met specialists throughout the world for their good words about my previous works, particularly the monograph *Forest Soils and Forest Growth*. The support and cooperation of the Wisconsin Conservation Department, the Wisconsin Alumni Research Foundation, the U. S. Forest Service, the Consolidated Water Power and Paper Company, and the Nekoosa-Edwards Paper Company made possible the accumulation of the major part of the original research data incorporated in this volume.

Finally, I wish to acknowledge my indebtedness to the asylum in Section 17, T. 39 N., R. 7 E., 4th P.M., and the patient, silent witnesses of my labors—slow running Brook and mottled Gley. Without these there would have been neither peace of mind nor book.

S. A. WILDE

Madison, Wisconsin
December, 1957

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I

SOIL AS A MEDIUM FOR TREE GROWTH

A new degree is taken in scholarship as soon as a man has learned to read in the wood as well as he reads in the study.

—Emerson, 1838

I went to the woods because I wished to live deliberately, to front only the essential facts of life, and see if I could not learn what it had to teach, and not, when I came to die, discover that I had not lived.
—Thoreau, *Walden* (1854)

1

Historical and introductory

RISE OF KNOWLEDGE

Unwritten records. Since time immemorial, the daily needs and inborn inquisitiveness of mankind have stimulated interest in the soils of the forest. The earliest observations of the relationships between soil and forest vegetation were made by the primitive forest dwellers. For many centuries Indians in North America and Mongolian tribes in Eurasia have had a remarkably clear concept of the adaptation and productivity of various soil types. The dependence of these people upon woodland crops led to an intimate understanding of the factors influencing the distribution of trees, shrubs, and ground-cover plants, the quality of wood, bark, and bast fibers, the susceptibility of forest to fire, and the occurrence of fur- and feather-clad inhabitants. This information was transmitted from father to son, and its final form represents the result of a multitude of collective experiences.

Speaking of the habitats of the Ojibway Indians, Smith (1932) states: "They recognize regular types of soil as sources of their medicinal plants. Sandy meadows . . . swamps, upland swamps, rocky openings in the forest, evergreen forests, and hardwood forests, all are searched for distinctive plants."

In many instances, the language of aborigines still casts a ray of light that illuminates the concealed relations of land and life. As related by Kruedener (1927), the terminology of natives inhabiting the Eurasian north served as a valuable guide to soil scientists and foresters in the early stages of their ecological research. In a single word primitive people have often synthesized the numerous characteristics of a soil-forest unit. For example, the word **muskeg** of the Algonquian Indians describes a stagnant swamp of strongly acid, nutrient-impoverished moss peat which supports slowly growing stands of black spruce and tamarack with a ground cover of leatherleaf, Labrador tea, cranberries, and other bog plants providing cover and sustenance for spruce grouse. Similar relationships are expressed by many other folk terms—**pocosins** and **chapparal** of America; **heath, moor, les landes,** and **macchie** of central and southern Europe; **sogra, nya-yag,** and **neva** of northern Europe (Morozov, 1912; Huikari, 1952).

Perhaps the oldest unwritten testament that bears witness to the profound insight of the people of the wilderness is the *Kalevala,* national epic of the Finns. This document was transmitted by wandering bards and storytellers for nearly 3000 years, until it was recorded by philologists in the nineteenth century in a volume of many hundred pages. In one part of the *Kalevala,* the hero Pellerwoinen takes upon himself the duties of the wind god and broadcasts seed of forest trees with a skill that may be envied by a modern ecologist: "Spreads the spruce seed on the mountains and the pine seeds on the hilltops; in the swamps he sows the birches, on the quaking marshes alder, and the basswood in the valleys; in the moist earth sows the willows, mountain ash in virgin places, on the banks of streams the hawthorn, junipers on knolls and highlands. . . ."

Early documents. Philosophers of earlier civilizations have frequently considered the problems of soils and forest growth (Glinka, 1931). An account of plant succession and the victory of forest vegetation over its eternal adversary—grass—was given about 70 B.C. by Lucretius in his volume, *On the Nature of Things.* The influence of soil and climate on the distribution of woody plants was outlined by Virgil in his *Georgics,* written during the first century B.C.: "Nor indeed can all soils bear things. By riversides willows grow, and alders in thick swamps, barren mountain-ashes on rocky hills; on the seashore myrtle thickets flourish best; and the god of the vine loves open slopes as yew trees do the freezing north . . . So diverse are the native lands of trees." Boethius (about A.D. 500) intuitively foretold the importance of nutrients in the life of trees: "Their mouths buried in the earth, they suck up nourishment by their roots and diffuse their strength through their pith and bark."

The contemplations on the nature of the universe, however, were terminated for more than a thousand years by the fall of the Roman Empire. Even in the course of the seventeenth and eighteenth centuries only a few works were published on the subject of soils and forestry. An outline picture of the literature of this period can be traced by the writings of Bacon (1627), Evelyn (1674), Carlovitz (1713), Réaumur (1721), Buffon (1739), Külbel (1741), Wallerius (1761), the Earl of Dundonald (1795), and Erasmus Darwin (1800).

Pioneer studies. The end of the Napoleonic wars brought a renewed interest in natural phenomena and the search for basic truths. Botanists and geologists, as well as foresters, began to contribute systematically to the knowledge of the soil factors of forest distribution and growth. Outstanding pioneer attempts to discuss soils in connection with silvicultural practices were made by Heinrich Cotta (1809), Hundeshagen (1830), Sprengel (1832), and Schubler (1838).

In 1840, the principles of soil science and ecology were introduced to silviculture by Grebe, a German forester. His doctor's thesis *On Conditions Essential for Sound Growth of Our Trees,* submitted at the University of Marburg, may well be considered as the cornerstone of forest soil science. The *Cotta's Forestry Album,* published in 1844, includes the following statement of Grebe, remarkable for its vision: "As silvicultural horizons widen, the importance of environmental conditions becomes more sharply pronounced. It appears clearly to the foresters that the form of forest management is determined by a number of physical influences related to topography, geology, type of soil, and climate."

Simultaneous publication of texts on forest soils by Grebe and B. Cotta in 1852 were followed by similar works of Heyer (1860), Senft (1867), and Girard (1868). At about the same time, on the other side of the Atlantic, two forerunners of American ecological studies appeared—a report by Cooper (1859) and one by Hilgard (1860).

In 1860 Pfeil, a German authority on forest management, published a book with an extensive chapter entitled "Science of Forest Habitat." The variation in the results of the same silvicultural operations obtained under different conditions of climate and soils led Pfeil to introduce his famous paradox: "The only general rule in forestry is that there are no general rules . . ." The publications of Grebe and Pfeil strongly influenced a number of texts on silviculture, particularly that of Emeis (1875) and the *Diagnosis of Forest Stands* by Gayer (1876).

Research in forest soils by Ebermayer, Müller, and Ramann had accumulated toward the end of the past century a great deal of factual knowledge. Ebermayer's *Study of Forest Litter* (1876) and *Scientific Foundations of Forestry and Agriculture* (1882) even today have not lost their significance. Müller's monograph on forms of humus (1878) revealed the biological nature of forest soils development. Ramann's text, *Forest Soil Science* (1893), consolidated the existing knowledge and outlined the general course of the subject. About the same time, Ramann's colleague in Munich University, Professor Mayr, published an extensive account on growth conditions of the North American forests (1890).

In 1879 Grandeau introduced the subject of soils to French foresters. In 1907 a comprehensive French monograph, *Forest Soils,* by Henry declared that "besides the agricultural pedology, there exists the forest pedology."

The discovery of the climatic-zonal principles of soil development opened new vistas in soil science and served to reorient the course of forest soils investigations. The findings of Dokuchaev (1879) and his associates, particularly Sibirtzev, Ototzky, and Kostychev, were enthusiastically received by Russian foresters. The beginning of the twentieth century was marked by intensive research in forest soils, led primarily by Morozov, Wissotzky, and Kruedener. Glinka (1908) observed in his widely known text on soils: "The abundant material collected by foresters on the relation of soils and forest vegetation exceeded by far that accumulated in regard to other types of vegetation. In the reports of Morozov and his followers the problems of soils are intimately welded to those of silviculture." Among the numerous students of soils in Russian forestry schools, Gedroiz (1912) cast a new light upon the relation of soils to plant nutrition by his investigations of colloids and exchange reactions. As Marbut (1936) stated, "In the pioneer chemical work of Gedroiz . . . with a previously unknown method real soil chemistry was created."

The Danish text by Warming on environmental requirements of plants, published in 1895, stimulated numerous studies in the field of plant ecology. The comprehensive work by Schimper (1898) is one of many others which could be mentioned. The investigations of ecologists provided an important link in the chain of studies on the relation of forests to environment. Two forest ecologists—Cajander (1909) of Finland, and Sukachev (1913) of Russia—devised botanical site classifications directly applicable to silvicultural practice.

A contribution of great importance to the knowledge of forest soils was made by Hilgard (1906). This geologist and soil scientist, concerned with agronomical problems, laid perhaps unintentionally the foundations of forest ecology. The chapters on the relation of native vegetation to soils in his text probably constitute the most valuable single document yet written on this subject. The general outlook of foresters in America was also strongly influenced by a number of ecologists, notably Merriam (1898), Cowles (1899), and Clements (1916). The general trend of contemporary American silvicultural practice was indicated by Toumey's *Foundation of Silviculture upon an Ecological Basis* (1916).

Recent developments. Thus, at the beginning of the twentieth century, the ranks of forest soil students included a significant number of men of talent who made original contributions to the knowledge of soil genesis, hydrological relations, and plant nutrition. The information accumulated in different parts of the world on soils supporting forest vegetation attained the form of a separate scientific discipline; the scope of its subject matter expanded to include several hundred volumes.

In spite of this progress, research in forest soils was conducted at this time not by special personnel but by volunteers who devoted their leisure time to the solution of the mysteries of forest life concealed below the ground line. These enthusiasts excavated pits, analyzed soil samples, and published reports. Meanwhile, practicing foresters carried on their long rotation management plans, cut trees, and planted seedlings without any attention to soil conditions. Occasionally, this uncoordinated activity crippled nursery stock by unbalanced fertilizer treatments, resulted in a discouragingly slow growth of trees on unsuitable soils, and terminated selection cuttings on hardpan soils by windfall. But these and other dramas in the daily life of forest management were usually accepted in a meek spirit of submission before the unpredictable forces of the elements.

The change in this situation came after World War I, when Germany, Austria-Hungary, and Russia had undergone not only political and social but also silvicultural revolution. Three events played a particularly important part in provoking the rebellion against the outmoded theories and empirical practices. They were destruction of vast areas of spruce stands on unsuitable sites by parasitic organisms, revelation, in records from Saxony, of a considerable decrease in the rate of growth of forests managed on the basis of abstract formulas, and a greatly increased productivity in forests of central Europe where the old management patterns had been discarded. Wiebecke (1920), Möller (1922), Wiedemann (1925), and many other German writers denounced the principles of stereotyped forest management. They proclaimed the correlation of tree growth with microclimate and soil as the road toward the solution of the "riddle of production."

These ideas soon penetrated far beyond the boundaries of Germany. They found wholehearted support among Russian, Scandinavian, and Finnish foresters, who from the early days of their silviculture recognized the importance of environment and were thus fortunately spared the disappointments of their continental neighbors. Most of the Swiss and French foresters adopted as a standard guide *Forest Management* by Biolley (1920), a book advocating the "coordination of all the forces involved in wood production" as the basis of sound silviculture and picturing the forest as "a tri-phased unit of soil, atmosphere, and wood-producing community." To a considerable degree the interest in forest soils was stimulated by the International Congress of Soil Science, held in 1927 in Washington, D. C.

The enormous reforestation program, undertaken as a public works project by the United States Government in 1933, served as a further strong impetus for investigation of forest soils. When many of the states launched a program of an annual production of millions of seedlings and reforestation of thousands of acres, the neglect of the soil threatened staggering financial losses. Fortunately, Americans lived in much closer contact with virgin soils and original vegetation than the people of western Europe. The basic relationship between the environment and plant growth had been noticed in the New World ever since the early days of colonization (Mayr, 1890). The knowledge gathered by the settlers and woodsmen was inherited by foresters and in a brief space of time integrated in silvicultural practice.

The subject of forest soils has gradually found its way into the forestry schools of the United States, and during the past twenty years no less than 200 theses on the nature and influences of forest soils were accepted by graduate divisions. Each of these dissertations was a foundation stone for the new building destined to replace the deteriorating structure of "soil-less" silviculture.

SOILS OF FORESTS: NATURE AND BEHAVIOR

Organic impulses: their rhythm and harmony. In the words of Lin Yutang, the outline of every tree "expresses a rhythm resulting from sunshine, the impulse to maintain its equilibrium, and the necessity of resisting the movement of the wind . . . The result is something perfectly harmonious and immensely satisfying."

The same law of organic impulses is indeed applicable to every aggregate of trees and shrubs, and to other forms of life that are collectively called *forest.* At the base of this natural coordination and harmony rests the soil, the medium that supports and nourishes different members of the forest community. The soil influences the composition of forest stands, their morphological pattern, rate of growth, quality of wood, reproductive vigor, degree of resistance to diseases, and stability against the wind. An understanding of the forest lies just as much below as above the ground line.

Composition of forest soils. As a natural body and a source of sustenance, the soil has earned many definitions, varying as widely as the background of their originators. In early writings of agronomists the soil was defined as "a mixture of sand, clay, lime, and humus." The geologists regarded soil as a "product of weathering derived from minerals and containing decomposed remains of plants and animals." Pioneers in soil science recognized that "the soil is the weathered surface layer of the earth's crust which has been altered by the influence of water, air, organic matter and living organisms." Because the changes produced by environmental and biotic agents lead to the translocation of soluble salts and colloids and the development of distinct layers, the soil was referred to as "a sequence of mutually interrelated horizons." The definitions formulated by biologically minded students characterize soil as "a peculiar organism" and "a dynamic system."

All of these definitions elucidate certain aspects of the soil, but none of them is entirely acceptable to a silviculturist interested in soil as a medium of forest growth. In many instances forested soils are products of weathering composed of sand and clay particles and arranged in genetic horizons. Very often, however, forests are supported by rock outcrops, piles of boulders, skeletal detritus, deposits of peat, water-suspended layers of quagmire, and even permanently flooded areas of bayous and mangrove swamps (Fig. 1–1). These types of forest lands, disregarded in general definitions of soil, are not rare exceptions; they cover vast areas in different parts of the world and at times provide sustenance to forest stands of high rate of growth and commercial importance. Obviously, the existence of such forest sites demands a broader concept of forest soils.

In brief terms, forest soil may be described as *a portion of the earth's surface which serves as a medium for the sustenance of forest vegetation; it consists of mineral and organic matter permeated by varying amounts of water and air and inhabited by organisms; it exhibits peculiar characteristics acquired under the influence of the*

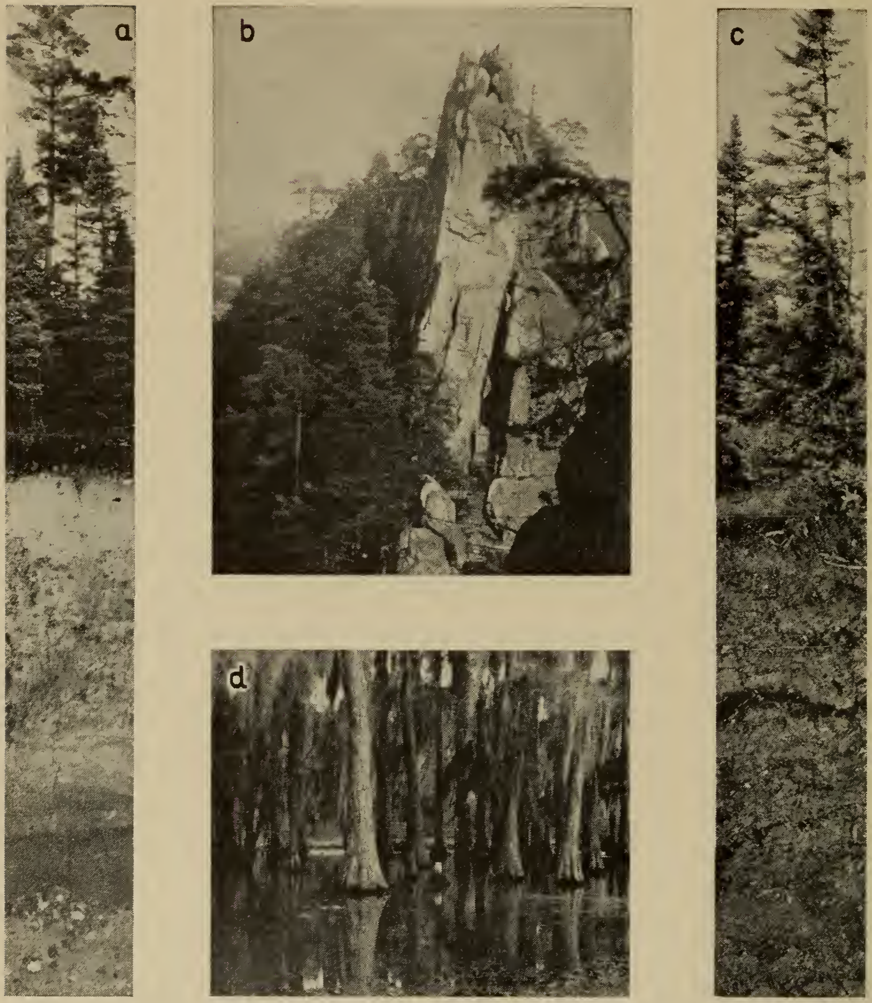


Fig. 1–1. Types of forest supporting substrata: (*a*) soil originated by weathering of rocks and accumulation of organic matter; (*b*) rock outcrops, the primitive type of forest soil; (*c*) moss peat, a holorganic forest soil; (*d*) submerged forest soil of a bayou.

three pedogenetic factors uncommon to other soils—forest litter, tree roots, and specific organisms whose existence depends upon the presence of forest vegetation.

Once acquired by the soil, these characteristics persist for many decades after forest cover has been removed and the soil subjected to cultivation. In some instances morphological properties, chemical composition, and even specific microorganisms have served as identifiable features of the forest soil origin after more than a century of continuous agricultural use of the deforested land. Therefore, the implication that one can speak one year of "forest soils" and another year of "corn soils" or "potato soils" is based on a gross misunderstanding of the genesis of forest soils and their inherent properties.

Because of their nature, forest soils exhibit all conceivable variations in their physical and chemical properties. In rock outcrops and skeletal soils of forested mountains, the root systems of trees may be the chief source of organic matter, since the litter in such locations is often removed by wind and water. The trees on such soils exist by "solid phase" feeding on unweathered minerals and by utilizing moisture condensed on the surface of rocks. On the other hand, in peat soils of swamps the mineral material constitutes but a small ash fraction of plant remains. The submerged roots on such soils must be satisfied with the oxygen and nutrients spared by ground water. Still other soils of forests are composed of mineral and organic fractions which include such extremes as boulders and ultramicroscopic clays, partly rotted logs and colloidal humate suspensions. Some of these soils consist of nearly pure silica and support struggling stands of the least exacting trees; other soils have a productive potential comparable to the richest blackearths of prairie regions and support tree species of high nutrient requirements (Table 1–1). Profiles of forest soils of different geologic origin and morphology are presented schematically in Figure 1–2.

The most important living constituent of forest soils is the root system of trees carrying beneficial mycorrhizal fungi which assist the trees in uptake of nutrients. The population of other organisms in forest soils varies from a small community of anaerobic and acid-tolerant microbes to a multitude of bacteria, actinomycetes, fungi, algae, protozoa, nematodes, worms, arthropods, moles, shrews, and rodents.

Soil and substratum. Soils form an essential part of the **biosphere**, the life-permeated zone encompassing the earth. In the picturesque language of Marbut, "The soil occupies a position in the twilight of life . . . It is a natural body in which the paths of the non-living mineral world and the living organic world cross."

The soil rests upon **abiotic** layers of the earth, devoid of life and referred to as the **dead substratum**. In spite of its sterility the dead substratum may profoundly influence the productive capacity of the soil; it may store water and nutrients which may be periodically transmitted to the root systems of plants by a capillary or a direct rise of ground water.

TABLE 1-1

APPROXIMATE COMPOSITION OF A SLIGHTLY ACID LOAM DERIVED FROM FELDSPATHIC ROCKS AND SUPPORTING A STAND OF HARD MAPLE, BASSWOOD, AND WHITE ASH (SURFACE LAYER)

<table>
<tr><td colspan="5">Solids
50% by volume</td></tr>
<tr><td colspan="3">Inorganic
93% by weight</td><td colspan="2">Organic
7% by weight</td></tr>
<tr><td>Sand
43%</td><td>Silt
35%</td><td>Clay
15%</td><td>Humus</td><td>Organisms</td></tr>
<tr><td colspan="2">Feldspar
Micas
Quartz and accessory minerals</td><td>Silica, kaolin
Iron and aluminum oxides
Clay minerals</td><td>Lignin
Cellulose
Sugars
Resins, waxes
Proteins, ash</td><td>Roots, bacteria
Fungi
Actinomycetes
Algae, protozoa
Nematodes
Earthworms
Arthropods
Insects
Rodents</td></tr>
<tr><td colspan="3">Liquids (30% by volume)
Dilute solutions of salts, acids, and gases</td><td colspan="2">Gases (20% by volume)
Air somewhat enriched by carbon dioxide</td></tr>
<tr><td colspan="3">Sulfates, nitrates, chlorides; bicarbonates of calcium, magnesium, potassium, and sodium. Traces of phosphates and other inorganic and organic compounds. Concentration of salts about 300 ppm.</td><td colspan="2">Oxygen 20.0%
Nitrogen 78.6%
Argon 0.9%
Carbon dioxide 0.5%
Traces of ammonia, hydrogen, and hydrogen sulfide</td></tr>
</table>

Depth of forest soils. The depth of forest soils is determined by the actual or potential penetration of tree roots. It varies from a few inches to many feet. Occasionally, the region of root distribution is sharply delineated by impermeable bedrock, by ground water, or by a soil layer containing chemical compounds toxic to roots. In other cases the depth of forest soil is neither a constant nor a definite feature; it depends upon the inherent ability of tree species and soil organisms to penetrate geologic strata.

Beyond certain limits the depth of the soil loses its ecological importance. In the vast majority of cases, examination of a soil to 4 or 5 feet is sufficient to reveal the features essential for tree growth.

Forest soils as a storehouse of energy. The energy transmitted daily from the sun to the earth is calculated in millions of horsepower. A portion of this vast quantity of energy is trapped by the photosynthesizing foliage of forest vegetation and is eventually incorporated into the soil as humus. The ability of forest soils to main-

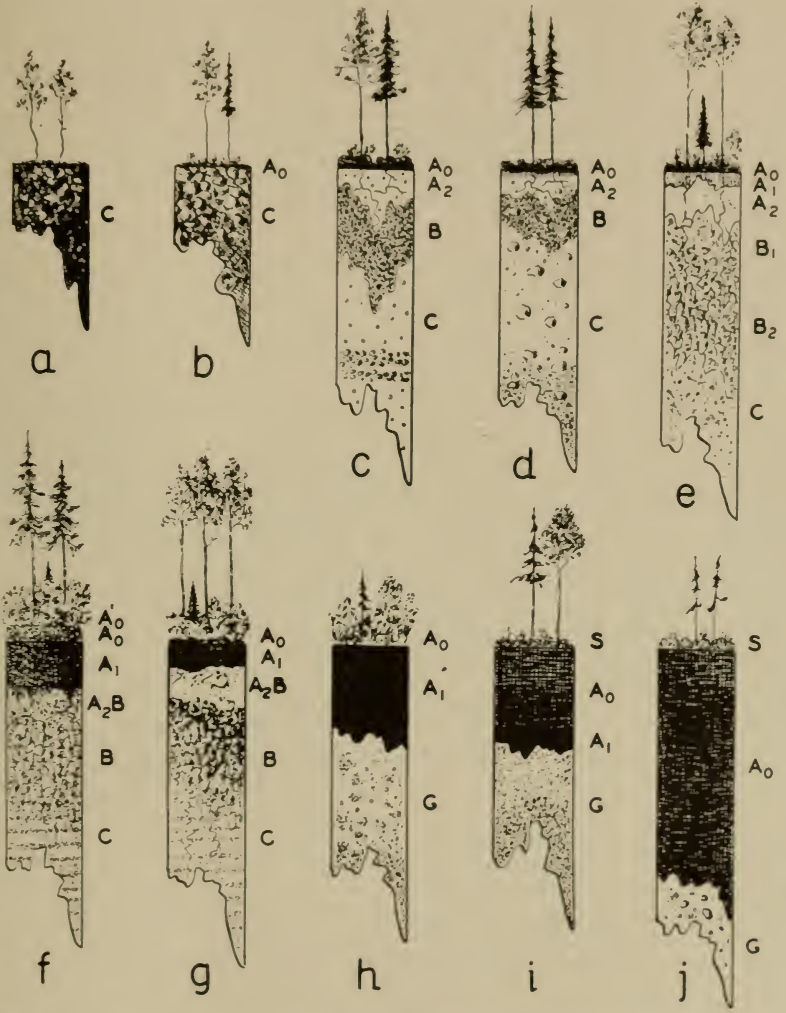


FIG. 1–2. Schematic presentation of typical profiles of forest soils: (*a*) outcrops of crystalline rocks; (*b*) granitic boulder pavement; (*c*) leached sandy soil of glacial outwash; (*d*) leached sandy soil of partly assorted coarse glacial deposit; (*e*) slightly leached loam of fluvioglacial loess-like outwash; (*f*) humus-enriched, structured clay of calcareous lacustrine deposit; (*g*) leached calcareous clay; (*h*) semi-organic muck soil of stream bottoms; (*i*) brown moss peat; (*j*) green or bog moss peat. Heights of the trees indicate the approximate productive capacity of the soils.

tain or even increase their supply of organic matter is probably the most essential feature distinguishing them from cultivated soils. The reforestation of abandoned farm lands in many cases is a long-time rotation of field and forest crops enforced by the depletion of soil organic matter.

Another source of energy for the body of the soil is the decomposition of minerals and rocks, endothermic compounds which were formed by crystallization from magma at a high temperature and pressure. In weathering of feldspars, for instance, as much as 120 calories may be liberated per gram of material. Of course, the energy released in weathering processes is very small in comparison with the energy of radiation.

Soils and silviculture. Forest soil is the medium that produces a unique multiple crop—an association of plants and animals distinguished by immense practical usefulness and by an infinite richness of patterns. According to Morozov, the forest is "man's most wonderful gift from nature." Millions of people throughout the world receive from the forest their daily bread, shelter, fuel, clothing, and numerous other commodities. With the progress in wood technology, forest products have penetrated every phase of life, and the possibilities of further developments are far from being exhausted. Regardless of population density and the availability of means and materials that may replace wood, the forest will continue to occupy its place of economic importance because of several conditions: it has a much greater capacity to utilize soil water and nutrients than do field crops; it is a faster producer of cellulose than any other association of plants; it requires minimum expenditure of human energy per unit area and allows mass production on extensive tracts.

The forest provides a number of benefits which cannot be reckoned in terms of dollars and cents. It controls erosion and conserves moisture which becomes the lifeblood of cultivated crops. Being an outlet for labor, the forest serves as a buffering agent, moderating disturbances of economic equilibrium in time of depression. The role of the forest as a social factor was remarkably outlined centuries ago by Gautama. In the words of the founder of Buddhism, "The forest is a peculiar organism of unlimited kindness and benevolence that makes no demands for its sustenance and extends generously the products of its life activity; it provides protection to all beings, offering shade even to the axeman who destroys it."

The planned production and utilization of forest crops, or silviculture, includes three major provinces of activity: (1) raising tree seedlings or "planting stock" in forest nurseries which are protected and often artificially irrigated areas with fertile soils; (2) reforestation, consisting of planting seed or nursery-grown seedlings on open lands or under protection of forest cover; (3) cutting of forest stands to reduce dense stocking, to obtain natural regeneration, or to remove trees that have reached maturity. The success of all these silvicultural operations depends upon a close coordination of the technique with the conditions of soils—soils of the nursery, planting site, or cutting area.

Soils of nursery beds. In order to succeed in growing seedlings year after year on the same area it is necessary to apply at regular intervals commercial fertilizers to feed the plants, and toxic substances to control parasitic fungi, destructive insects, and noxious weeds. All of these chemicals enter into reactions with the soil constituents, and some of them cause destruction of not only the harmful but also the useful organisms. Under such circumstances the productive capacity of a soil may be maintained only if the intricate chemical and biological interrelationships are thoroughly understood and properly adjusted.

The seedlings remain in the nursery for one or more years, during which period they are supposed to attain the necessary vigor to survive under the adverse conditions of the planting site. The characteristics seedlings acquire in the period of their early development in the nursery often decide the fate of plantations. If the planting stock is raised in an unsuitable soil and is lacking in vigor, one of two results may be expected: either the seedlings will die shortly after being transplanted, or they may struggle for a number of years and eventually become hosts for parasitic organisms. Such struggling plantations present a great danger in artificial reforestation because they provide the breeding centers from which parasites may invade forest stands throughout the region.

The expense involved in purchasing and applying disinfectants and fertilizers in some nurseries amounts to several hundred dollars per acre. This expense, however, is well justified, considering the high value of the product. One acre of a forest nursery produces more than a million two-year-old seedlings. The minimum cost of two-year-old seedlings, according to present price lists of private companies, is $10 per thousand. Thus, the gross income from one acre of nursery soil in two years amounts to at least $10,000; the gross income of a nursery 40 acres in size may reach $250,000 per year. One acre of a forest nursery produces enough seedlings to reforest 1000 acres and, consequently, the care given to a forest nursery of average size may decide the future of forest stands worth millions of dollars.

Soils and tree-planting. The importance of soil characteristics is rather obvious in reforestation because the failure or stagnant growth of plantations soon follows indiscriminate tree planting. The ultimate aim of reforestation practice is not the mere survival of trees but the establishment of forest stands that will resist parasitic organisms, regenerate freely, and produce high yields of valuable timber. This can be accomplished only by carefully matching soil conditions with requirements of tree species.

Because reforestation is practiced on large acreages and is a long-term investment, negligence in the selection of planting sites may result in huge financial losses. An outright failure of a 40-acre plantation represents, at present prices, a financial loss of about $1000. Survival of a plantation of similar size on an unsuitable soil and its subsequent inadequate growth for a period of fifty years may bring the total losses to the staggering figure of several thousand dollars, owing to expenses for taxes, silvicultural care, and interest on the investment.

Soils and silvicultural cuttings. The maximum direct and indirect benefits from a forestry enterprise can be attained only by management on a sustained yield basis or by "use without abuse." The technique which usually satisfies this requirement is skillful silvicultural cuttings perpetuating the uninterrupted existence of a forest. The conditions of soil play an extremely important part in this phase of silvicultural practice. The cuttings which are based only on the above-ground features of forest stands may ruin the natural fertility of soil, initiate soil erosion, or alter adversely the level of ground water. Such cuttings seldom assure the success of natural reproduction. In the opinion of Koroleff (1935), a Canadian forest scientist, "the forester cannot intelligently select even a more or less suitable cutting stencil from his book collection unless he has an adequate theoretical and practical knowledge of various forest soils and of the whole complex relationship between these and the life of the various trees and other plants of the forest . . . The knowledge of the underground life of a forest is the only key to adequate understanding of its above-surface life."

One of the most important features of selection cutting is that the removal of even a few trees changes the conditions of light, temperature, and moisture. These changes produce radical modifications in the state of ground-cover vegetation, soil organisms, and, in turn, in the composition of the soil. To achieve the most favorable end result the forester must be able to grasp the entire course of the chain reactions between the climate under the stand canopy, the living and nonliving constituents of the soil, and the forest cover—its growth and its regeneration capacity.

Forest soils versus farm soils. Forest soils cover about one-half of the entire land surface and are bounded by soils of tundra, marshes, heaths, grasslands, and deserts. Approximately one-fifth of the total forest soil area is occupied by farms, although as much as one-third has potential agricultural possibilities. The remainder comprises so-called "absolute forest lands," which include soils unsuitable for agricultural use, such as those of high mountains, rough and stony tracts of glacial deposits, and acid peat bogs.

Fortunately for both agriculture and silviculture, soil requirements of farm and forest crops are vastly different, and their production is usually possible without undue competition for the land. As often as not, agriculturally excellent soils support stands of oak, hickory, hard maple, and other hardwoods that produce less than 10 Mbf per acre of inferior timber. Conversely, agriculturally worthless bleached soils of sandy texture, strong acidity, and other seemingly unfavorable characteristics may support stands of white pine which yield as much as 100 Mbf per acre of high-grade lumber. If at the present level of prices, the maximum stumpage value of many stands on the hardwood loams in $150 per acre, the stumpage value of the white pine stand on podzolized sand could be $1000

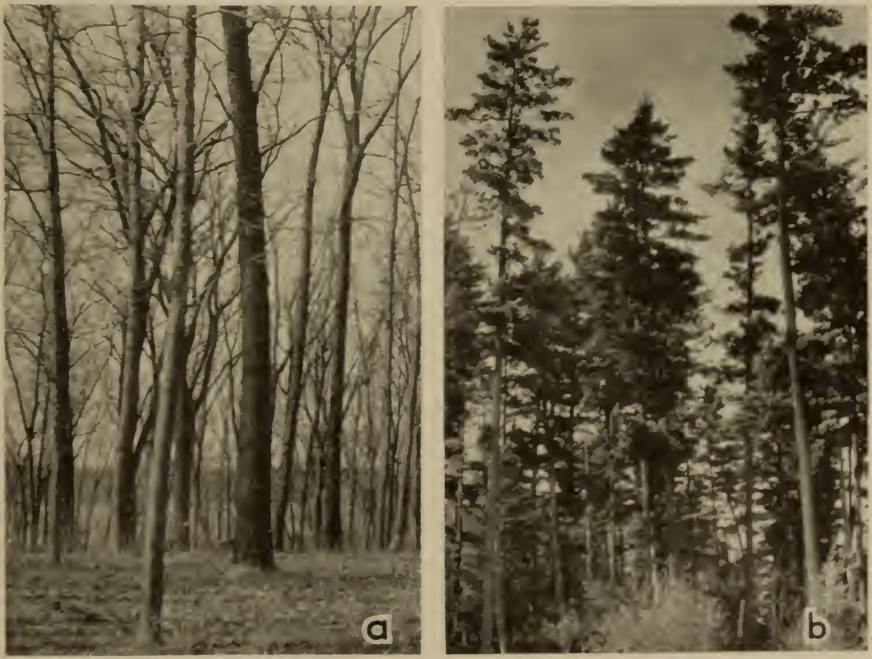


FIG. 1-3. Comparison of the productive potential of soils under forest crops. (*a*) Exacting hardwoods of a fair growth on one of the world's most productive soils, silt loam of calcareous drift in southern Wisconsin; the yield of a fully stocked stand at 100 years is about 12 Mbf per acre. (*b*) White pine of excellent growth on a coarse leached sandy soil of glacial outwash in northern Minnesota; the yield of a fully stocked stand at 100 years is nearly 50 Mbf per acre.

or even $2000 per acre. Hence, choice land for farming purposes may be mediocre or even poor land for forestry purposes; conversely, agriculturally unproductive lands of boulder-littered moraines, rough and gravelly deposits of pitted outwash, and semiswamp grounds may be the prize lands for silvicultural endeavors (Fig. 1–3).

Although the techniques of silviculture and farming are not comparable, many basic problems of field crop production, soil analysis, and application of fertilizers may, according to Hilgard (1906), be approached more successfully by the study of *objectum naturae*—virgin forest soils, rather than *objectum artis*—soils distorted by cultivation. The conditions which make forest cover a unique indicator of soil productivity are the presence of many tree species, characteristic ground vegetation, and the permanent record of the stand's growth written by the heights of trees and the annual rings of the stems. To these attributes of forest cover, soil science is indebted for a great deal of information pertinent to the nutrition and water requirements of plants.

2

These are passages for study. The more they are distasteful, the better I shall be pleased. I have striven to make them so.
—Leopold Mozart,
father of Wolfgang

From rocks to soils to forest cover

WEATHERING AND THE LIFE CYCLE

In the words of Fallou (1862), "the tooth of time incessantly grinds the crust of our planet . . ." Under the influence of physical, chemical, and biotic agents of weathering, the solid mass of the earth is broken into fragments of rocks and their building blocks—minerals, soluble salts, bases, and acids. Either *in situ* or after relocation by gravity, water, and wind, the products of weathering become the prey of plant roots and microbes. Thus, after millions of dormant years in the earth's crust, the ions of essential nutrients enter the cycle of organic life.

The length of the stay of nutrient ions above the ground is determined by many conditions: climate, topography, nature of the soil, and form of land utilization. Some of the ions find their way into blades of grass only to be plowed under in the fall; the next spring runoff of a torrential rain may carry them down the valley, down the river to be buried again in a sedimentary rock formed on the bottom of the ocean. Other ions may be trapped by the feeding roots of a tree and chained to the ever-turning wheel of forest soil fertility; their destiny will be to travel ceaselessly from foliage of plants to cells of microorganisms, to soil solution, and back to the foliage. No one has excelled Aldo Leopold (1949) in the description of the fate of the indestructible wandering ion:

> *X* had marked time in the limestone ledge since the Paleozoic seas covered the land. Time, to an atom locked in a rock, does not pass.
>
> The break came when a bur-oak root nosed down a crack and began prying and sucking. In the flash of a century the rock decayed, and *X* was pulled out and up into the world of living things. He helped build a flower, which became an acorn, which fattened a deer, which fed an Indian, all in a single year.
>
> From berth in the Indian's bones, *X* joined in chase and flight, feast and famine, hope and fear . . . When the Indian took leave of the prairies, *X* moldered briefly underground, only to embark on a second trip through the blood-stream of the land . . .

To grasp the mechanism of the life cycle, the relationship between the dead inorganic world and the living organic world, one must acquire knowledge of the solidified portion of the globe, or the lithosphere—its morphology, internal structure, physico-chemical characteristics, and dynamic changes caused by the forces of environment. The properties of important minerals, rocks, and surface geologic formations are outlined in the following descriptions. A more detailed discussion can be found in the geology texts by Bowman (1911), Emerson (1928), Thwaites (1946), Longwell *et al.* (1949), and Thornbury (1954).

SOIL-FORMING MINERALS; THEIR CHARACTERISTICS AND VALUE AS SOURCES OF PLANT NUTRIENTS

The lithosphere is composed of more than ninety elements, but only fourteen form the bulk of the earth's crust. These are oxygen (O), hydrogen (H), carbon (C), phosphorus (P), sulfur (S), chlorine (Cl), silicon (Si), aluminum (Al), iron (Fe), manganese (Mn), calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). With a few exceptions, these elements are combined in the form of minerals. The latter occur as separate bodies or as natural aggregates, called rocks.

Minerals are largely products of cooled magma and evaporated solutions. As a rule, magmatic cooling and evaporation brought about crystallization of various chemical compounds in fixed shapes such as cubes, rhombohedrons, and prisms terminating in pyramids. The crystals are not always symmetrical, but they have definite interfacial angles and their form is constant for a given mineral. In fact, the form of a crystal presents an outward expression of the internal atomic or ionic makeup of the mineral (Fig. 2–1). Thus the hexagonal shape of quartz (SiO_2) is the result of a small four-valent atom of silicon surrounded by large bivalent atoms of oxygen. Similarly, the regular cubic form of triclinic potassium feldspar ($KAlSi_3O_8$) owes its origin to the symmetrical arrangement of silicon, aluminum, potassium, and oxygen atoms. The most conspicuous manifestation of the fanciful behavior of ions is revealed by micas; the perfect horizontal cleavage and foliated shape of these minerals are caused by a sheetlike arrangement of silicon, aluminum, and oxygen atoms.

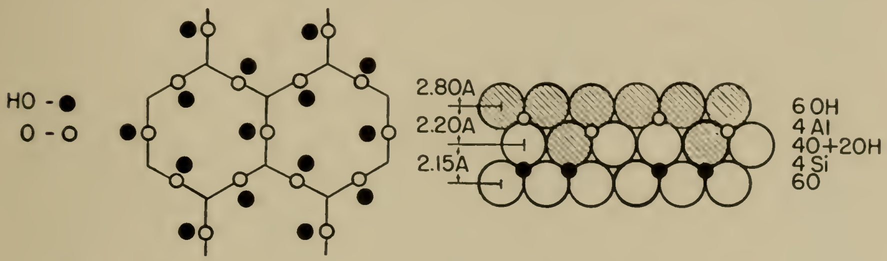


FIG. 2–1. Arrangement of silicon, aluminum, oxygen, and hydroxyl atoms in kaolinite.

The relationship of chemical bonds and crystal formation is one of the most fascinating details in the mineral structure of the earth, a detail which often brings not only the soil, but even the mineral substratum into the "twilight of life." This subject is treated by special monographs, such as those of Bragg (1937), Pauling (1939), and Marshall (1949).

Besides their chemical composition and crystal form, minerals are characterized by color, luster, cleavage, streak, tenacity, fracture, hardness, and specific gravity. Unfortunately, many of these characteristics are too uncertain to be of value in field investigations. Crystals incorporated in rocks usually appear to the naked eye as irregular grains, aggregates, or deformed masses. The true color of minerals is often obscured by impurities. The scratch test of hardness is applicable in rare cases. Specific gravity is a reliable and important property of minerals, but its determination requires special laboratory equipment. All in all, the forester and the soil surveyor must be satisfied with a limited and empirical knowledge of the most common minerals. Such knowledge is acquired largely by observing marked mineral specimens isolated and imbedded in rocks.

The following description outlines the major features of the important soil-forming minerals and stresses their value as potential

TABLE 2–1

CHEMICAL COMPOSITION, HARDNESS, AND SPECIFIC GRAVITY OF IMPORTANT SOIL-FORMING MINERALS

Mineral	Composition	Nutrient elements	Hardness	Specific gravity
Quartz	Silica, SiO_2	None	7	2.65
Orthoclase, potassium feldspar	Potassium aluminosilicate, $KAlSi_3O_8$	K	6	2.56
Plagioclase, lime-soda feldspars	Ca- or Na-aluminosilicates	Ca	6	2.68
Muscovite, potassium mica	K-aluminosilicate with OH group	K	2	2.85
Biotite, iron-magnesium mica	K(FeMg)-aluminosilicate with OH group	K, Mg, Fe	2	3.01
Chlorite	Aluminosilicate with Mg and Fe	Mg, Fe	2	2.75
Glauconite, "green sand"	Hydrated KFe-aluminosilicate	K, Fe, (Ca)	2	2.30
Amphibole, hornblende	CaMgFe-silicate	Mg, Ca, Fe, (K)	5	3.22
Augite	CaMgFe-silicate	Mg, Ca, Fe	5	3.40
Olivine	FeMg-silicate	Mg, Fe	6	3.41
Serpentine	Mg-silicate	Mg	3	2.60
Calcite	Calcium carbonate, $CaCO_3$	Ca	3	2.72
Dolomite	Calcium-magnesium carbonate, $CaMg(CO_3)_2$	Ca, Mg	3	2.90
Gypsum	Hydrated calcium sulfate, $CaSO_4 \cdot 2H_2O$	Ca, S	2	2.30
Apatite	Calcium fluorophosphate, $Ca_5(PO_4)_3F(Cl)$	P, Ca	5	3.20
Hematite	Iron oxide, Fe_2O_3	Fe	6	5.25
Limonite	Hydrated iron oxide, $Fe_2O_3 \cdot 2H_2O$	Fe	(5)	3.80
Magnetite	Iron oxide, Fe_3O_4	Fe	5	5.20
Siderite	Ferrous carbonate, $FeCO_3$	Fe	4	3.80

sources of plant nutrients. Approximate chemical composition and certain physical characteristics of minerals are given in Table 2–1.

Quartz is a form of silica, of white to drab color and glassy luster. Its prismatic six-sided crystals have no lines of cleavage and break with a conchoidal fracture. It is harder than all common minerals, is insoluble in acids, except hydrofluoric, and is slightly soluble in alkalies.

Quartz is the most common soil-forming mineral and occurs largely as round or angular grains, either transparent or coated with red or yellow iron oxides. It is resistant to weathering, has no value as a plant nutrient, and forms the inert coarse fraction or "skeleton" of soils. Some sandy soils of glacial outwash and wind-blown deposits have as much as 98 per cent of quartz.

Amorphous forms of silica include translucent **chalcedony**, dark-colored **chert**, and spark-producing **flint.**

Orthoclase is potassium feldspar, or potassium aluminosilicate, of white to red color, nearly as hard as quartz, and with well-defined cleavage at angles of about 90 degrees.

Potassium feldspar is a widely distributed soil-forming mineral and an essential constituent of granite and related feldspathic rocks. It weathers at a fairly rapid rate and serves as the principal source of potassium in soils. The products of weathering include kaolinite and other clay minerals which possess the ability to retain and exchange the ions of hydrogen, ammonium, and bases.

Plagioclase is calcium-sodium feldspar of white to dark gray color and distinct cleavage. It has the same hardness as potassium feldspar and can be scratched by quartz. Plagioclase and its related varieties, such as **oligoclase, labradorite,** and **anorthite,** occur predominantly in ferromagnesian rocks. They weather more readily than potassium feldspar and serve as sources of calcium.

Muscovite is potash mica, or potassium aluminosilicate, containing the hydroxyl group. It is crystallized in the form of white or light brown folia which can be scratched with the thumbnail and are known as "isinglass." Potash mica is a widely distributed mineral, abundant in granite and schists. It is a source of potassium but weathers with difficulty and does not contribute greatly to the nutrient supply of soils. Upon hydration it may acquire ability to retain positively charged ions and thus be transformed into clay minerals of the **illite** group.

Biotite is iron-magnesium mica, crystallized in the form of black or brown folia, known as "black mica." This common ingredient of feldspathic and ferromagnesian rocks is similar to muscovite but weathers more readily and supplies potassium, magnesium, and iron. In some instances, abundance of biotite is correlated with soils of favorable physical conditions and high level of fertility.

Chlorites are closely related to micas but are not elastic and yield no nutrients except magnesium. The knowledge of chlorites is important chiefly because they are essential constituents of chlorite schists, rocks known to produce infertile soils.

Glauconite is hydrated aluminosilicate of iron and potassium, usually enriched in calcium and other bases. This soft mineral occurs usually in the form of greenish grains, the so-called "greensand." Being a source of potassium and other nutrients, glauconite increases the fertility of siliceous soils derived from fluvial deposits and shales.

Zeolites or "boiling stones" are light-colored, unstable hydrated silicates of the approximate formula $R(SiO_3)_x \cdot nH_2O$. They swell and lose their combined water upon slight heating, thus imparting to water the appearance of boiling. These minerals possess the capacity for cation exchange, but because of their instability are rarely found in soils. Originally the term "zeolites" was applied to clay minerals.

Clay minerals include **kaolinite, montmorillonite, hydrous mica** or **illite**, and several other aluminum and iron silicates containing bases and hydrogen. These minerals are white or yellow crystallo-colloidal products of weathering of different silicate minerals, especially feldspars and micas.

Clay minerals have a more or less pronounced hexagonal or platy shape and some have an internal lattice structure. The latter property permits clay minerals to expand on contact with water and to provide landing berths for positively charged ions cruising in the soil solution. In this way, clay minerals play an extremely important function in soil fertility; they serve as storehouses for nutrients, particularly calcium, magnesium, potassium, and ammonia.

According to earlier beliefs, kaolinite was the principal mineral of the clay fraction responsible for retention of cations. However, improved analytical techniques have established that kaolinite plays only a minor part in adsorption of nutrients and exchange reactions of soils. Montmorillonite and related minerals appear to represent the most active colloidal fraction, possessing the highest capacity to lodge successive groups of different ions. Hydrous micas, or minerals of the illite group, occupy an intermediate position and have a somewhat lower cation exchange capacity.

Amphibole, augite, and **olivine** are heavy ferromagnesian silicates of black, dark brown, or green color, nearly as hard as feldspar and not easily cut with a knife.

These essential constituents of ferromagnesians or "basic" rocks tend to decompose readily and yield soils with an abundant supply of calcium, magnesium, potassium, and iron. Augite resists weathering more than other members of this group and in some soils is present as "black gravel." Hornblende is the most widely distributed form of amphiboles; at times its dark color as well as its high content of nutrients give rise to dark and fertile forest soils which resemble prairie blackearths. Olivine is a related mineral which imparts its greenish color to many eruptive rocks.

Serpentine is a soft and greasy hydrated magnesium silicate of mottled green color. It is easily cut with a knife. The ecological importance of this impoverished product of weathering of ferromagnesian minerals rests in its unfavorable properties; soils derived from serpentine rocks are noted for their shallowness, poor physical make-up, and unbalanced content of nutrients. "Serpentine barrens" is an expression which is not confined to the English language.

Calcite or calcium carbonate is a colorless, brown, or red vitreous mineral with a distinctive rhombic cleavage. It effervesces with cold dilute hydrochloric acid and can be scratched with a copper coin but not with a thumbnail.

Calcite is the essential constituent of limestone soils. It produces an alkaline reaction and plays a far-reaching role in the process of soil development and in plant nutrition. Depending on its relative proportion in soil material and on climatic conditions, calcite exerts either highly beneficial or detrimental effects on forest growth. It is a natural fertilizing agent for correcting soil acidity and calcium deficiency.

Dolomite or calcium-magnesium carbonate is a white and glossy to dull mineral, slightly harder and more resistant to weathering than calcite. It effervesces only in hot hydrochloric acid. Dolomite is a common associate of calcite and occurs in many limestone rocks and soils. It is an important natural fertilizing material for soils depleted in magnesium and calcium.

Gypsum is calcium sulfate combined with water. This colorless massive or crystalline mineral is very soft and can be scratched with a thumbnail. It is slightly soluble in water and, when heated, gives off its combined water to form "plaster of Paris."

Gypsum accumulates below the zone of carbonates in grassland soils of semiarid regions. It is used to decrease toxic alkalinity of soils by converting sodium carbonate to sodium sulfate.

Apatite or calcium fluorophosphate is a brown, green, or black moderately hard mineral that barely scratches glass. An important source of phosphorus, it occurs locally in extensive deposits but more commonly in the form of small crystals incorporated into a wide variety of rocks. The solubility of apatite and the release of phosphorus in the form available to plants are enhanced by water charged with carbonic acid. With certain modifications, this process is imitated in the preparation of phosphate fertilizers.

Hematite is iron oxide of earthy appearance and a red or brownish red color resembling that of blood. It is characterized by a cherry-red streak and is slightly softer than glass.

Hematite is common in feldspars and ferromagnesian rocks. It also occurs as red coating on sand and as cementing material, particularly in the accumulative soil layers. The red color of this mineral serves as an indication of oxidizing conditions and position of the ground water table.

Limonite is hydrated iron oxide of a compact earthy structure, yellow to light brown in color, and somewhat softer than hematite. It occurs as common "iron rust" and imparts to soils a yellowish color indicating oxidizing conditions.

Magnetite or "lodestone" is another iron oxide characterized by high specific gravity, metallic luster, and black streak. The major importance of this constituent of many crystalline rocks is its ability to deflect a compass needle and thus mislead a surveyor of forests or soils.

Siderite or ferrous carbonate is a green or gray to black mineral somewhat harder than calcite. It occurs chiefly in waterlogged strata of soils to which it imparts a greenish color, a characteristic indicative of deficiency of aeration and reducing conditions.

Mineralogical Analysis; Its Importance in Soil Studies and in Silviculture. The identification of soil minerals attains its greatest significance in investigations of the colloidal fraction of soils. This fraction possesses an enormous surface area of many square miles per gram of material and has the ability to retain exchangeable ions. As recent studies have shown, this effect of soil colloids is intimately related to the content of different clay minerals, such as montmorillonite and hydrous micas.

The determination of the mineralogical composition of the noncolloidal fraction of soils has a certain importance in the evaluation of silvicultural possibilities of the land. Soils containing a high percentage of the so-called "light" minerals, whose specific gravity is below 2.68, usually have a lower potential fertility than the soils enriched in "heavy" minerals (Tamm, 1934, 1937). This is because light minerals largely include quartz, which has no value as a plant nutrient. The separation of soil on the basis of specific gravity is usually confined to the particles ranging from 0.2 to 0.6 mm. in diameter. Analysis of this type, however, provides only very general information on the potential productive capacity of soils.

Occasionally a forest soil specialist is requested to locate deposits of rocks or minerals which could be used as fertilizing material for forest nurseries or plantations. This is largely true of calcium- and magnesium-bearing deposits, feldspars high in potassium, and some ferromagnesian rocks, particularly basalt. The first step in the solution of this problem is a reconnaissance survey of potential sources of plant nutrients, made on the basis of a general familiarity with minerals and rocks. After suitable deposits are found, their content of plant nutrient elements must be established by laboratory analyses, a task requiring the services of a soil specialist or a chemist.

SOIL-FORMING ROCKS: THEIR PROPERTIES AND THEIR WEATHERING PRODUCTS

Minerals are external manifestations of exacting physico-chemical relationships. Rocks are more or less incidental and heterogeneous aggregates of minerals formed by the consolidating effects of temperature, pressure, and inorganic agglutination. Depending upon their mode of origin, rocks are divided into three groups: igneous, sedimentary, and metamorphic.

Igneous rocks were formed during the solidification of a molten magma by fusion of two or more unaltered minerals. Typical representatives of this group are granite and basalt. The former is a coarse-grained aggregate of orthoclase, quartz, and mica; the latter is a fine-textured compound of plagioclase and augite.

Sedimentary rocks were produced either by cementation of deposited minerals, rock fragments, and shells of organisms, or by precipitation of salts from solution. The cementation of quartz sand deposits produced sandstones, consolidation of sedimented calcareous shells gave rise to limestones, and precipitation of hydrous calcium sulfate originated gypsum.

Metamorphic rocks are igneous and sedimentary rocks which have been compacted, recrystallized, or otherwise altered by the action of heat, pressure, and water charged with salts, acids, and gases. Gneiss is a granite which attained a laminated structure under the influence of pressure and heat, marble is a crystallized limestone, and quartzite is a sandstone impregnated by an infiltration of silica.

IGNEOUS ROCKS

The members of this group are classified on the basis of their textural and mineralogical composition (Fig. 2–2).

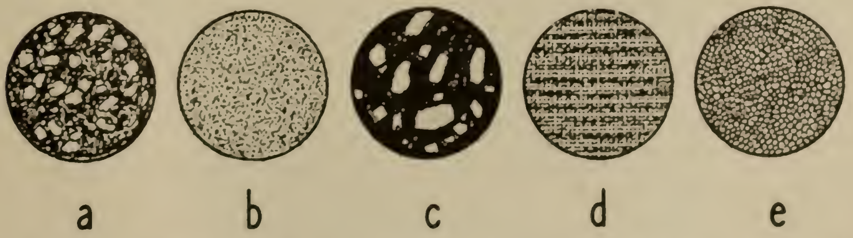


FIG. 2–2. Texture of rocks: (*a*) granitoid, typical for granite, gabbro, and diorite; (*b*) felsitic, characteristic of felsites, trachyte, and basalt; (*c*) porphyritic texture of granite or gabbro porphyry; (*d*) foliated texture of gneiss; (*e*) single-grained texture of sandstone.

Rocks of granitoid texture. This group includes rocks whose interlocking crystals are large enough to be distinguished by the eye.

Granite is a name applied to a widely distributed class of rocks composed of orthoclase and other feldspars, quartz, micas, and occasionally amphibole and augite. The color of these rocks varies from light gray to red. The expression "rock of granite" is associated in the human mind with firmness and resistance against the destructive forces of the environment. But, in time, even granite succumbs to the assaults of raindrops, microorganisms, and plant roots. Feldspar, micas, and accessory minerals are weathered into clays and only quartz is left as coarse grains. The end product is soil material of a sandy loam or loam texture, carrying some phosphorus and a high content of potassium but often a small amount of other bases.

Syenite is similar to granite except that it has little or no quartz. It weathers more readily and gives rise to fine-textured soils.

Diorite represents dark-colored or greenish-black rocks, made up principally of hornblende and feldspar. These rocks give rise to heavy clay or clay loam soils that are very low in quartz.

Gabbro is a term embracing dark, coarse-textured, heavy rocks composed of calcium feldspar and augite with a small amount of quartz. At times the accessory minerals of gabbro include magnetite in a quantity sufficient to influence a compass needle. Weathering of these rocks yields fine-textured soils generously supplied with calcium and magnesium.

Peridotite is composed entirely of ferromagnesian minerals with olivine predominating.

Figure 2–3 gives the relative proportion of minerals composing different igneous rocks.

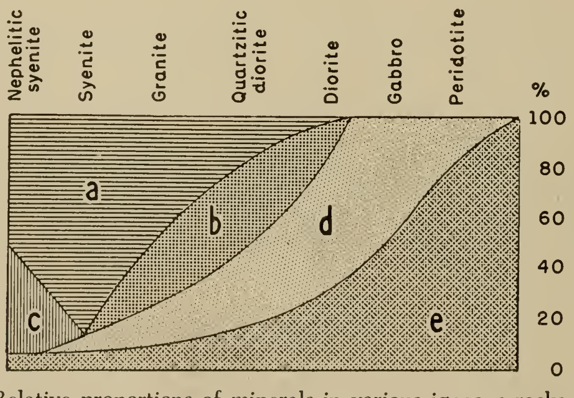


FIG. 2–3. Relative proportions of minerals in various igneous rocks: (*a*) feldspar; (*b*) quartz; (*c*) nepheline; (*d*) plagioclase; (*e*) ferromagnesian silicates. (From P. Principi, 1953.)

Rocks of felsitic texture. This group includes rocks whose individual crystals are too small to be visible to the naked eye.

Felsite is the term applied to light-colored, fine-textured rocks composed chiefly of feldspar. Being of volcanic origin, felsites are hard, resist weathering, and tend to produce shallow soils.

Rhyolite is a variety of felsite exhibiting bands and streaks common to lava flows. This rock is noted as parent material of poor, gravelly, and porous soils.

Trachyte is a felsitic rock composed largely of feldspars and containing little or no quartz. It weathers at a slow rate and often produces infertile soils deficient in calcium and magnesium.

Basalt is a dark-colored and heavy ferromagnesian "trap" rock, similar to gabbro in composition but of a fine texture. It does not weather readily and tends to produce shallow and rocky soils which nevertheless are well supplied with nutrients. When sufficiently weathered, basalt yields soils of exceptionally high fertility.

Andesite is a rock similar to basalt except that it has a very low content of quartz.

Rocks of porphyritic texture. This group includes fine-textured felsitic rocks exhibiting large crystals or "phenocrysts" imbedded in the ground mass. Depending on the nature of the ground mass or of the phenocrysts, rocks are classified as "granite porphyry," "syenite porphyry," "gabbro porphyry," "quartz porphyry," and "feldspar porphyry." Porphyritic texture is a morphological detail which is of minor importance in the process of soil development and forest growth.

Rocks of glassy texture. Rocks of this type were formed by a rapid cooling of magma, which precluded crystallization.

Obsidian is the term that describes hard, brittle glassy rocks, usually of a dark color. By and large, these rocks are siliceous in nature, but in some instances they are enriched in iron and bases and are classified as "andesite obsidian," "basalt obsidian," etc. Regardless of their mineralogical makeup, obsidians weather very slowly and yield shallow, infertile soils. Fortunately, the distribution of these rocks is very limited.

Pumice is a product of the capricious behavior of volcanoes; it is a spongy, vesicular lava that floats on water and is best described as "glass froth." In the regions of volcanic activity pumice sometimes forms deposits that serve as tree-supporting substrata. On the Pacific coast of the United States soils derived from pumice serve as sites for rapidly growing stands of Douglas fir and other conifers.

SEDIMENTARY ROCKS

Both the identification and the ecological appraisal of sedimentary rocks are much easier than those of igneous rocks. The value of different indurated sediments as soil-forming material is usually a resultant of the texture of rocks and of their mineralogical composition.

Sandstones are sediments of quartz sand particles consolidated by pressure and cementing material. The coherence and other properties of these rocks are determined by the nature of the cement, which may be silica, iron oxides, or lime. The cementing material, together with "impurities," exerts a decisive influence on the productive capacity of soils derived from sandstones. Sandstones cemented by iron and free from accessory minerals yield very infertile soils. Siliceous cements produce durable rocks which weather slowly into infertile, shallow, and stony soils. Calcareous cements enrich weathered debris in colloids and nutrients and give rise to deep and reasonably fertile soils. Sandstones are often porous and harbor artesian waters.

Conglomerates are deposits of gravel and other fragments of rocks cemented similarly to sandstones. Under the influence of weathering, they disintegrate into gravelly sands or sandy loams. The state of fertility of these soils is largely determined by the mineral composition of the parent deposit.

Siliceous shales are laminated, impermeable rocks formed by consolidation of siliceous silt and clay sediments. These rocks are readily fragmented by changes in temperature, but their chemical weathering is very slow. Soils derived from siliceous shales have fine texture, but a very low content of nutrients, sufficient only for the least exacting farm or forest crops. Siliceous silt loams and clays may be regarded, therefore, as impostors of productive lands; they have been responsible in the past for many dramas in the daily life of agriculture and silviculture.

Limestone is a consolidated deposit of clay, sand, and chert, enriched in calcium carbonate and accessory minerals. It is usually of white or gray color but may have light-brown or reddish tints imparted by iron oxides. The carbonate fraction of limestone is derived from calcareous skeletons or shells of mollusks and other sea organisms; in some instances, however, calcium carbonate is a precipitate from solution.

The relative density or hardness of limestone as well as the content of clay and accessory minerals are the factors which determine the productive potential of limestone soils. Pure limestones undergo a rapid weathering but produce infertile soils deficient in several essential nutrients, particularly phosphorus and potassium. Hard limestones resist weathering and tend to produce shallow and skeletal soils. This is especially true of cherty limestones. The most fertile soils are derived from soft limestones rich in clay and accessory minerals; these types of calcareous rocks were largely responsible for the claims that "limestone soils spell prosperity."

Dolomitic limestone is a rock containing the double carbonate of calcium and magnesium. It is similar in appearance to calcitic limestones but weathers at an appreciably slower rate and has a tendency to form knolls and ridges in calcareous regions. Dolomitic limestone often gives rise to skeletal and porous soils, but no generalizations can be made concerning the soil-forming value of this rock. At times dolomitic limestones produce exceedingly poor soils deficient in nutrients and supporting scanty vegetation. On the other hand, these rocks underlie highly productive soils on extensive areas of the American Midwest.

Calcareous rocks are usually identified by their ability to effervesce with cold hydrochloric acid. The dolomite, however, releases its carbon dioxide only in a heated acid solution. This difference in the behavior of the two minerals permits a simple analytical appraisal of magnesian limestones.

Chalk is crumbly limestone composed of microscopic shells. Its comparative freedom from impurities is responsible for the development of poor soils deficient in nutrients.

Calcareous shales are hardened siliceous deposits enriched in lime and at times interstratified with layers of sandstone or siliceous shales. They weather into fine-textured soils, often containing skeletal material of flat plates. The productive capacity of soils derived from calcareous shales varies within wide limits depending upon the depth of the shale layer, its content of carbonates, the presence of accessory minerals, and the nature of interstratified sedimentary rocks. In general, however, parent soil material of calcareous shales encourages the occurrence of exacting tree species and stimulates the rate of forest growth.

METAMORPHIC ROCKS

With few exceptions the effects of heat, pressure, and other factors of metamorphism served to reduce the taxonomic and ecological heterogeneity of igneous and sedimentary rocks. At the same time, processes of metamorphism usually brought about appreciable deterioration in the soil-forming values of the altered rocks.

Gneiss is a laminated or foliated metamorphic rock similar in composition to granite and related plutonic rocks. It is often referred to as "banded granite." The structure of gneiss facilitates its physical disintegration, but chemical weathering depends upon the mineralogical composition of the rock; quartz and muscovite tend to retard weathering, whereas feldspars and biotite have an opposite effect. The soils derived from gneiss resemble those derived from granitic rocks; they are of sandy loam or loam texture and often contain a considerable percentage of quartz gravel.

Schists are fine-grained or foliated rocks of widely different composition; however, they usually contain a large percentage of mica and some ferromagnesian minerals. Most schists break down readily under the influence of changing temperature, but they do not always undergo complete weathering and tend to produce soils with skeletal material. Schists abundant in mica give rise to so-called "micaceous" sandy loams. In many instances, soils originated from schists have a "greasy" feel, a result of the presence of talc.

The productive capacity of schist soils is influenced not only by the structure and chemical composition of the parent rock but also by the orientation of schistose layers. Horizontally oriented schists impede the entrance of water, whereas inclined strata discharge water as seepage.

Slates are dense, fine-grained rocks produced by the compression of shales. The metamorphism is usually accompanied by an increased hardness of the rock and its enrichment in micas and quartz. In the early stages of weathering, slates yield shallow, skeletal soils consisting of platy fragments and presenting an inhospitable medium for plants. But time, the all-powerful factor of weathering, changes even these resistant rocks into reasonably productive silt loams. As with schists, the orientation of slates may influence the soil moisture regime.

Quartzite is metamorphic sandstone, impregnated by infiltration of silica and enormously resistant to weathering. The root systems of forest vegetation armed with mycorrhizal fungi, however, can clasp inert outcrops of quartzite and extract from them a meager diet provided in part by wind-blown silt and clay lodged in the cracks. In many instances quartzite outcrops remain barren and dominate the landscape in their sterile grandeur.

Marble is a metamorphic limestone of a crystalline structure which possesses a great resistance to weathering. This unique medium which embodies and preserves beauty has a very low ecological value. Unluckily for art, but fortunately for plant growth, its distribution is very limited.

GEOGNOSY, PEDOLOGY, AND SILVICULTURE

The relationship between the geological origin of soils and forest growth is one of the most confused issues of forest ecology. Early students of forest soils believed that soil-forming rocks exert decisive influence on the distribution and growth of forest vegetation. Accordingly, soils were classified as "granitic," "dolomitic," "siliceous," and the like (Fallou, 1862). Classifications of this kind were supported by examples illustrating the effect of parent rocks.

At a later date, however, it was revealed that the influence of climatic factors may drastically alter the composition of the surface weathered layers. Thus, humid conditions may impart an extremely acid reaction to soils derived from highly calcareous rocks or may convert a rich ferromagnesian material into a residue of hydrated iron and aluminum oxides. On the other hand, in regions of moderate rainfall, purely siliceous deposits may acquire substantial layers of humus and a fair level of fertility. These observations led some soil scientists to suggest that the origin of parent material is of little significance in the development and composition of soils (Glinka, 1931). Such a claim obviously called into question the importance of a geological approach to soil classification. Actually, as the result of these implications, pedologists stampeded from geology to climatology (Marbut, 1928). Nevertheless, the replacement of one broad generalization by another failed to eliminate the controversy existing in textbooks as well as in nature. The reconciliation of the antithetical viewpoints under such conditions cannot be reached by the arbitrary adherence to either school of thought, but only by careful analysis of the relationships between the mineral substrata and vegetative cover under diversified physiographic conditions.

It is an ancient axiom that out of nothing comes nothing. Hence, soil material of pure quartz, a mineral of no value as a plant nutrient, could not give rise to a crop-producing soil. This postulate, however, would be true only in an ecological vacuum. Under natural conditions, a deposit of pure quartz is exposed to transient birds and animals, atmospheric dust, and rainwater bearing nitrogen from electric discharges. No matter how small the amount of mineral nutrients contributed by these agents, in time the deposit will be suitable to harbor algae, lichens, and nitrogen-fixing bacteria, then to be invaded by some higher plants, and finally to support jack pine yielding a dozen cords of pulpwood per acre.

This brief account is given to underscore the fact that mineral substratum cannot be divorced from environment. The validity of this statement can be further demonstrated by a review of vegetative cover found on similar deposits in different climatic regions.

Soils derived from calcareous rocks in South Dakota are black-earths devoid of trees. Soils of the same geologic origin in southern Wisconsin are occupied by stands of oak and hickory usually producing 10 Mbf per acre. Petrologically similar soils in northern Ontario support dense forests of spruce yielding as much as 30 Mbf per acre. Therefore, the plant-producing capacity of a parent soil material cannot be evaluated as a separate item but only as an integral part of a certain climatic milieu. A soil derived from a similar calcareous material may be unfavorable to forest vegetation in a dry climate but greatly beneficial in a humid climate.

A glance at the maps of the world's climatic regions and the distribution of native vegetation reveals that extreme conditions of either temperature or moisture completely neutralize the ecological influence of geologic substrata. The landscape of deserts preserves its uniform monotony over every kind of rock and deposit. Similarly, the tundra maintains the same cover of mosses and low shrubs across parent materials of the entire circumpolar zone. Even in regions of more favorable climatic conditions, such as those of prairies, northern coniferous forests, or tropical rain forests, the vegetative cover does not always react conspicuously to geologic variations.

A different picture, however, is observed when the temperature and moisture attain a reasonable balance and level off extreme differences between percolation and evaporation of soil water. Under such conditions the products of weathering enjoy a certain stability in the soil profile, and hence the composition of the soil parent material is reflected by vegetative cover. This relationship is most pronounced in the region of mesophytic deciduous forest, characterized by a mild, moderately warm and moist climate. The effect of parent rocks on the growth of plants is also obvious in certain portions of the mountains, where erosion constantly rejuvenates the surface soil layer and thus brings root systems in contact with a fresh supply of weathered debris. If for some reason the processes of denudation and deposition become arrested, the influence of percolating water and other soil-forming factors may in time completely alter the inherited composition of the weathered layer. *Consequently, the ecological effects of the parent soil material are like concentric ripples from a stone cast in a pool of water; they diminish with distance from the temperate climate and with the age of the soil.*

This analysis should help to explain the seemingly irreconcilable differences between the adherents of geological and pedogenetical approaches to soil classification. The former originated in the mountain-intersected by generally mild environment of central Europe, a geographic province where geological material indeed exerts a profound influence on soils and forest growth. The latter emanated from the plains of northern Europe and Siberia, regions in which superhumid or semiarid climates often erase the effects of substratum.

Considering the restrictions and amendments imposed by climate, topography, and age of the land, the soil-forming rocks may be grouped into four major ecological divisions, as originally suggested by Tamm (1921).

Siliceous rocks. These rocks, including **sandstones, siliceous shales, conglomerates,** and **quartzites,** generally produce soils which are poor in nutrients and of a low exchange capacity. Such soils are suitable primarily for less exacting tree species, particularly pines. A cementing material of lime or clay at times considerably raises the productive capacity of these soils.

Orthoclase–feldspathic rocks. Such rocks as **granite, syenite, granitic porphyry, orthoclase felsites,** and **gneiss** weather into sandy loam or loam soils well supplied with potassium and phosphorus but low in calcium and magnesium. These soils are well adapted to all timber-producing trees with the exception of a few lime-demanding species. In warmer climates the scarcity of bases is a highly welcome feature which reduces the incidence of root-rot diseases, especially those of conifers. Granite and its relatives are often described under a misnomer—"acidic" rocks. Substrata of this kind are neutral, and their soil offsprings acquire pronounced acid reaction only in humid climate or under coniferous stands.

Ferromagnesian rocks. These include **gabbro, diorite, diabase, basalt, andesite,** and **schists** enriched in augite, amphibole, or olivine. Youthful soils of this origin are often shallow, skeletal, and subject to drought. Upon sufficient weathering, ferromagnesian rocks yield fine-textured soils with an abundant supply of calcium, magnesium, phosphorus, and other essential nutrient elements. Considering the nutrient requirements of trees, the relatively low content of potassium of these soils may only in very rare instances decrease their high level of fertility. In warmer climates, ferromagnesian substrata impart to soils a nearly neutral or alkaline reaction. This favors the growth of exacting lime-demanding hardwoods but is presumably responsible for root rot of conifers, particularly spruce. In cold and humid climates deep soils of ferromagnesian origin are known to support exceptionally good stands of deciduous as well as coniferous species.

Calcareous rocks. Limestone, dolomitic limestone, chalk, and **calcareous shales** give rise to soils of greatly variable productive potential, determined by climatic conditions, degree of weathering, and content of clay. Deep soils derived from clay-rich limestones are among the most productive soils of cold and humid regions where they often support fast-growing stands of spruce and other so-called "acidophilous" conifers. In temperate regions such soils support lime-tolerant hardwoods and conifers, such as black walnut, hickory, white and green ash, beech, white elm, black locust, red cedar, white cedar, ponderosa pine, Austrian pine, and Douglas fir. Calcareous soils of a shallow depth, or those derived from pure limestones and chalk, often constitute the "problem lands" of forestry; in regions of low rainfall, such soils do not provide even submarginal sustenance to forest vegetation and are occupied by grass. The deficiency of potassium and phosphorus, the high content of carbonates, and the alkaline reaction are among the adverse factors that occasionally may be responsible for the malnutrition of trees, their chlorosis, and the incidence of root-rot and damping-off diseases.

Soils derived from calcareous rocks are predisposed to erosion and fixation of nutrients, particularly phosphorus, iron, manganese, and other trace elements. These soils, therefore, are most sensitive to the loss of organic matter.

STRUCTURAL FEATURES OF ROCKS

In many instances soil development and plant growth are strongly influenced by the structural features of rocks, such as joints, cleavage planes, dips, dikes, and sills.

Joints are crevices more or less perpendicular or parallel to the rock surface. **Cleavage planes** occur in shales, sandstones, and schists and often lead to the development of crevices. **Dip** refers to the angle that the slope of a formation makes with the true horizontal. Steeply dipping shales and schists allow the penetration of roots and moisture along the exposed cleavage planes, whereas horizontal beds do not. These features greatly influence the productivity of overlying shallow soils. Land slippage is likely to occur when the soil surface approximately parallels a steep dip surface.

Dikes are more or less vertical fissures which originally were below the surface of the earth and were later filled with molten rock; they often remain as ridges or hills when the less resistant overlying rocks have been eroded. Sills were formed when the magma was injected between rather than across the enclosing rock strata. Sills may form the resistant cap rock that gives rise to buttes and mesas.

Sedimentary and metamorphic rocks are often folded, **anticline** and **syncline** being the terms for, respectively, convex and concave folds. Over the convex anticline the rocks are stretched and often shattered, leading to more rapid erosion than in the adjacent syncline. **Faults** are breaks along which rocks have slipped; a **fault scarp** is the steep up-throw side of a major fault.

In rolling or rough topography the orientation of geological strata leads to pronounced differences in the moisture content of soils. When sloping terrain intersects the ascending geological strata, it is called a **scarp** or **strike** slope. Such slopes are usually impoverished in moisture content because a considerable part of the precipitation is carried away by the fissures of rocks. On the other hand, when the terrain intersects the declining strata of geologic formations, it is called a **dip** or **seepage** slope. Such slopes are enriched in water traveling along the fissures of the rock formation (Fig. 2–4).

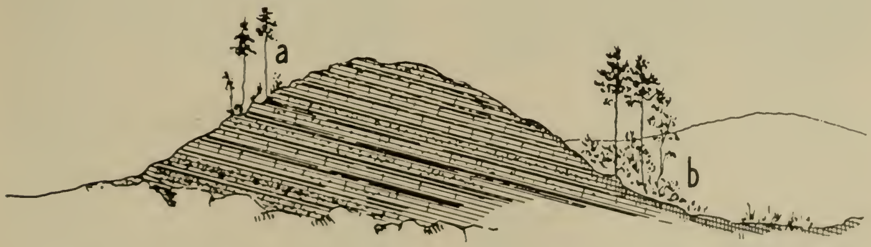


FIG. 2–4. Effect of inclined geologic strata on the moisture content of soil and on tree growth in rolling topography: (*a*) scarp slope, impoverished in moisture; (*b*) seepage slope, enriched in moisture.

SURFACE GEOLOGIC FORMATIONS AND RESULTANT SOILS

The forces of gravity, wind, ice, and water, acting on the weathered fragments of rocks, gave rise to various deposits. These, together with the stable portions of the earth's crust, constitute the surface geological formations. These formations impart to the soils many important characteristics and form a convenient basis for a broad soil classification (Fig. 2–5).

Rock outcrops and mantle rocks. Within forest regions, the occurrence of rock outcrops is largely confined to high mountains, steep slopes, and denuded areas. Root systems of trees clasp the

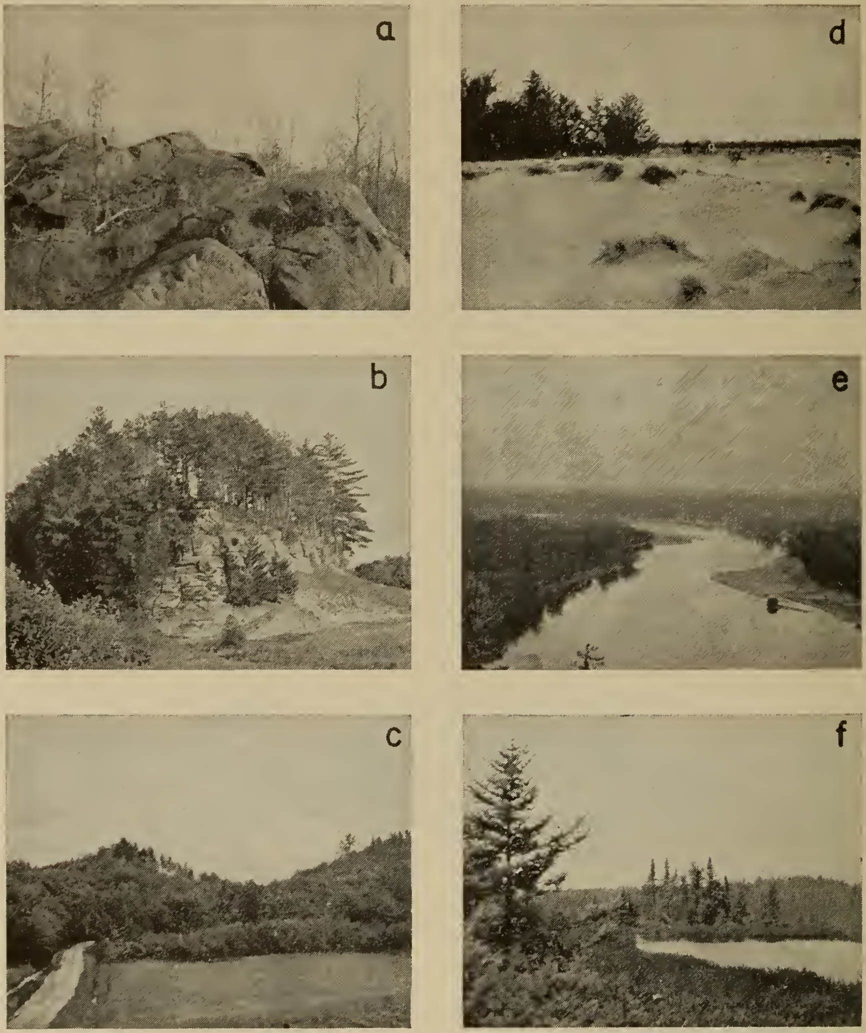


FIG. 2-5. Forest soils of different geologic origins: (*a*) rock outcrops; (*b*) residual soil derived from sandstone with talus at the foot of the knoll; (*c*) level glacial outwash grading into terminal moraine; (*d*) wind-blown sand; (*e*) flood-plain soils; (*f*) cumulose deposits surrounding a shallow glacial lake.

rock surface and penetrate through the fissures, thus changing barren strata into **rock outcrop soils** or **lithosols.** In accordance with mineralogic composition, granitic, sandstone, limestone, and like varieties of rock outcrop soils are recognized.

If conditions of climate and gradient permit, weathered material accumulates *in situ* as **mantle rock** or **residuum** which offers forest vegetation a more favorable foothold. Residual soils vary in depth, texture, and chemical composition, depending upon their age and character of their parent material. Young residual soils consist of slightly weathered, coarse detritus, or **regolith,** which grades at a shallow depth into **bedrock.** The chemical composition of such soils is often the same as that of the underlying substratum. Old residual soils are characterized by a greater depth and more finely divided particles. These soils have been subject to oxidation, hydration, and leaching for a long period, and the chemical composition of their surface layers may differ essentially from that of the parent material (Fig. 2–6).

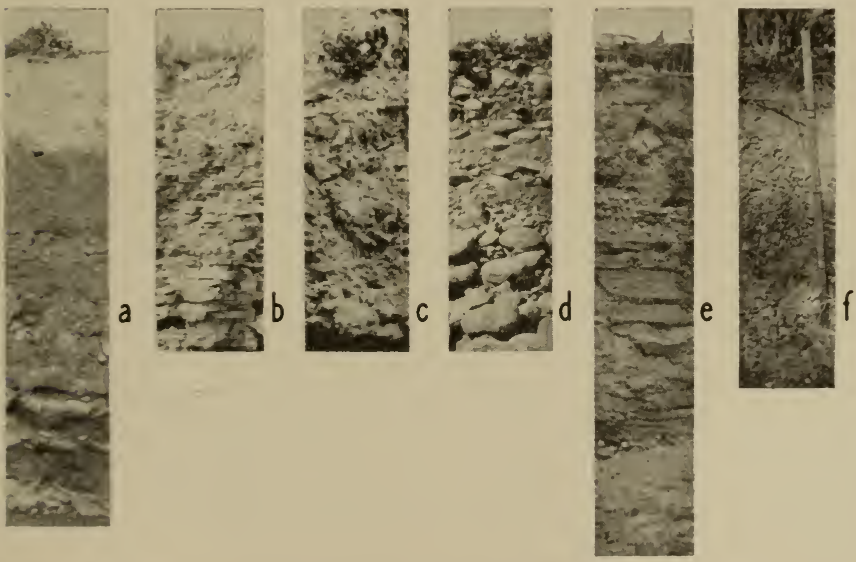


FIG. 2–6. Profiles of soils of different geologic origins: (*a*) deep clay loam originated by weathering *in situ* from Algonquian schist; (*b*) shallow residual silt loam derived from limestone; (*c*) loam of ground moraine; (*d*) stony and gravelly sandy loam of terminal moraine; (*e*) silt loam of glacial outwash underlain by an assorted substratum of sand and gravel; (*f*) clay of a lacustrine deposit.

In some instances residual soils are derived, not from the underlying substratum, but from material of a rock which has undergone weathering. Under such conditions the soils "inherit" certain properties from the preexisting rock and are called **inherited soils.**

Talus is the term referring to the coarse-textured **colluvial deposits** formed by fragments of rocks detached from the precipitous outcrops and carried down the slope by gravity. **Cliff debris, rock falls,** and **avalanches** are typical examples of rough and droughty talus soils. From a silvicultural standpoint, such soils may differ little from the rock outcrops.

Glacial deposits. The invasion of ice sheets brought about fundamental changes in the surface geology of the glaciated regions. The glaciers displaced the surface soils, ground the underlying rocks, and deposited **unassorted till.** The water from the melting ice took up some of the deposited debris and laid it down again as **stratified drift.** The hummocky ridges, accumulated in front of the invading ice, formed **end moraines** or **terminal moraines.** Along the sides of the glacial lobes were deposited **side moraines** or **lateral moraines,** and **interlobate moraines.** Periodic retreats of the ice produced **recessional moraines,** similar to end moraines but often arranged in a series of lobes. The ice movement compressed some material beneath it and in melting left scattered detritus, thus forming the **ground moraine.** In the regions of the ground moraine the movement of the glacier sometimes gave rise to **drumlins** or "whalebacks," oval-shaped smooth unassorted knolls with their long axis parallel to the ice movement.

The soils developed on the ground moraines are characterized by a fairly level topography, often shallow depth, and protruding polished rocks called "sheep backs." The smooth topography and the presence of impervious strata at shallow depths are often responsible for poor drainage of the ground morainic soils. The soils of terminal and recessional moraines are of rough topography, with embedded pebbles and boulders, and have widely variable proportions of sand and clay particles; they rest upon compact **unassorted till** or **boulder clay.** Because of the diversified topography and irregular occurrence of clay till, the drainage of these soils may vary greatly within short distances. The soils of drumlins are similar to those of ground moraines.

Fluvioglacial deposits. The streams and floods from the melting ice sheets carried in suspension eroded material which was gradually deposited, forming the **glacial outwash** or a series of **fans.** The **level outwash** was produced by uniform sedimentation of gravel, sand, and sometimes silt over the flat areas, usually at some distance from the terminal moraine. **Pitted outwash,** with its characteristic rolling topography and **kettle holes,** resulted from the melting of ice blocks embedded in the deposit, or from the deposition of material over the rugged surface of the morainic border. **Outwash terraces** are high bench remnants of fluvioglacial valley fills.

Soils of glacial outwash are predominantly of sandy or silt loam texture; other types occur in rare instances. At a depth of one or more feet, the surface layer usually grades into stratified coarse sand and gravel. The usual freedom from stones, level or undulating topography, and a low cost of road construction are important features of outwash soils.

Fluvioglacial deposits of limited distribution include kames and eskers. **Kames** are partly assorted gravelly hills or mounds accumulated by melt waters in ice caves under the glacier. **Eskers** are winding ridges of irregularly stratified sand and gravel deposited by subglacial streams. The soils of kames and especially those of eskers are often coarse and droughty.

Lacustrine deposits. These are sediments of previous lake bottoms. They form level beds of sand or clay with gentle slopes of sandy material marking the original shore line. Lacustrine clays are usually high in carbonates but are often deficient in both surface and vertical drainage. Most of the lacustrine soils are confined to glacial regions.

Marine deposits. These are sediments which once formed the bottom of the sea. Their texture varies from sand to clay, depending on the depth of water at the time of deposition and the force of the current. Skeletons or shells of animals often enrich marine sands and "muds" in calcareous material.

Alluvial deposits. The action of streams in the postglacial period produced three major types of deposit: stream beds, floodplains, and river terraces. **Stream bottom deposits** occur as narrow strips along creeks. A high content of organic matter and the presence of ground water near the surface are common features of stream bottom soils. **Floodplain deposits** are a result of the periodic overflow of rivers. The soils of floodplains are often sandy in the proximity of the river but grade into loams or clays farther from the river. This is because the velocity of flood waters decreases from the streams to the limits of the flooded area. The drainage is likely to be adequate near the river but sluggish at a distance from it. The periodic inundations enrich floodplains in organic matter and soluble salts. **River terraces** are level or nearly level strips of land bordering floodplains. They result from the dissection of previous stream beds and are classified as "second bottom," "third bottom," and so forth. The soils of river terraces contain less organic matter and soluble salts and are better drained than floodplain soils.

Overwash deposits. Overwash is formed on the lower slopes of hills and mountains by the deposition of material eroded from the upper slopes. Soils of overwash, as a rule, have a greater depth, a finer texture, and a higher content of humus and nutrients than the residual soils of the upper denuded areas.

Aeolian deposits. The action of wind produces two sharply defined types: loess and blow sands. **Loess** is a uniform deposit of comparatively unweathered silt of yellowish buff color. It varies in depth from a few inches to nearly a hundred feet. The soils of loessial origin have nearly ideal physical properties and a very high potential fertility. Their geographic distribution, however, does not always coincide with climatic conditions favorable to forest growth. **Blow sands** develop where the stabilizing vegetative cover of sandy soils has been destroyed. In places they form sand dunes which may be over 100 feet deep and may advance over a region at a rate of nearly 100 feet per year. Wind-blown sands lack colloidal material and are deficient in both moisture and nutrients.

Cumulose deposits. The cumulose or "piled up" deposits are formed by the remains of vegetation accumulated in shallow water basins or on uplands of the high mountains and subarctic regions. The deposits of this nature include various types of peat and muck. Lowland prairie or meadow soils may also be considered cumulose deposits. Forest soils of cumulose deposits are deficient in drainage and often poor in nutrients.

Figure 2–7 illustrates the relation between the geologic features and soils.

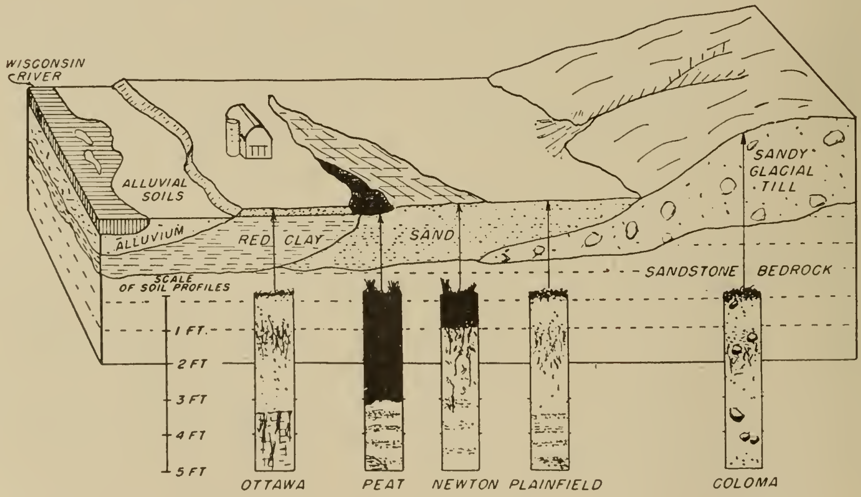


FIG. 2–7. Schematic illustration of the relationship between soils and geologic features. (Dr. F. D. Hole, Wisconsin Soil Survey.)

> *The role of the infinitesimally small organisms appears to be infinitely great.* —Louis Pasteur

3

Organisms of forest soils

SOIL AS A BIOLOGICAL ENTITY

Organisms and soil development. Regardless of the nature of the soil parent material and the intensity of the weathering processes, the abiotic strata of the earth represent only a soil-forming potential, not the soil. The birth of a soil as a natural body and a productive medium takes place when the lifeless geologic matrix is invaded by organisms: first, autotrophic and photosynthesizing; later, heterotrophic, either saprophytic or parasitic. In time all these life forms combine in a definite community whose life activity, metabolic by-products, and dead remains are instrumental in the development of the soil. It is not without reason that the many variations encountered in the definition of soil are always hinged to the same common theme:.soil's living constituents and their residues. While environment, in all its manifestations, influences the course of soil development, the organisms serve as a tool with which nature fashions both the visible morphological pattern and the concealed physico-chemical properties of soils. It is a general trend, almost a law of soil biology, that the smaller the size of the organism, the larger its number, the more specific its function, and the greater its influence on soil properties.

Through biological aspects soil science is linked with the names of great scientists, such as Leeuwenhoek, Darwin, Pasteur, Beijerink, and Winogradsky. In spite of this, soil biology still includes many blind areas which are especially frequent in the realm of forest soils—a realm in which the activity of organisms presents the greatest theoretical interest as well as practical importance.

Energy material and its transformations. The ground under the forest canopy is constantly enriched in leaves, fruit husks, twigs, and other remains of trees and lesser plants. Quadrupeds, amphibians, birds, and insects—all walking, creeping, crawling, and flying creatures—contribute to the surface layer of forest soils the products of their metabolism and their dead bodies. This residue of life of plants and animals becomes the source of life for other organisms, organisms of minute size, ephemeral existence, and immense accomplishments. They devour the deposited energy material and after its digestion release simple inorganic compounds to promote the all-important process of photosynthesis, the manufacturing of fresh supplies of organic matter.

Few events on our planet can match in complexity and immutable wisdom the drama performed on the forest floor and inside the forest litter by the legions of beetles, larvae, centipedes, millipedes, ants, sow bugs, ticks, mites, nematodes, rotifers, protozoa, and many creatures too small to be seen. All of these are engaged in destruction, metabolism, reproduction, and mortal struggle to free the world from piling-up organic remains.

The efficiency with which leafmold workers dispose of dead material is graphically described by Jacks (1954): "I have seen a pine forest in which recently pruned branches covered the ground loosely to a depth of three feet or more; in an adjoining section similarly pruned five years before, although nothing had been removed, there was scarcely a trace of the prunings to be seen. Everything had been decomposed, and the forester who had lived among such things all his life naturally saw nothing remarkable in them. Yet it is inconceivable that if those tree branches (some several inches thick) had been spread in an open field they would have disappeared so completely. The forest fauna and microflora, however, dealt with them without difficulty."

How numerous and efficient are the organisms employed in turnover of organic matter can be judged from the fact that spiders alone annually kill in England and Wales more than 200 billion insects; their weight exceeds that of the human population of Great Britain (Crompton, 1954).

Much of the labor on decomposition of crude organic leftovers is performed in a very inconspicuous and unspectacular manner by the sluggish members of the leafmold community, the fungi. In the words of Jacot (1953), "This complex is rendered more intricate by the growth of minute fungus molds which feed upon the dead leaves and organic refuse, weaving it all into a compact mat by their myriad white hyphae. Thus is the woof woven into the warp of the woodland rug." In the final result the woof of microbiological activity is woven into the warps of genetic soil development, nutrition of forest vegetation, and the life of the entire forest biome.

Classes of forest soil organisms. The rating of organisms influencing forest soils invariably poses puzzling questions. What are the soil organisms proper? At what size does a microorganism become a macroorganism? Which organisms are beneficial and which are harmful?

From the standpoint of forestry practice, the June beetle in the larval stage is one of the most important soil organisms, but upon becoming an adult it forsakes its underground quarters. Livestock are not soil organisms, but they produce drastic alteration of forest soils on an immense total area of farm woodlands. Many of the worms are microscopic in size, but those inhabiting the soils of Australia and Madagascar attain gigantic dimensions of several feet in length and several inches in diameter (Glinka, 1931). Some arthropods have lively colonies in a single spruce needle; others attain the respectable size of a few inches. The worms, because of their soil-cultivating habits, have gained a wide fame as benefactors of mankind—a fame which completely overshadows their subversive activity as destroyers of foliage and roots of natural forest reproduction, especially that of spruce (Shiperovich, 1936).

These are the reasons why, in practical evaluation of the activity of woodland flora and fauna, one must at times abandon conventional divisions and rigorous taxonomic patterns. The most important organisms of forest soils are the root systems of trees and other plants. However, these members of the subterranean world have thus far been in the class of untouchables for the authors of most books dealing with soils. In this text the description of woodland organisms is arranged in the following interrelated groups: roots, bacteria, fungi, actinomycetes, algae, protozoa, worms, arthropods, birds, and mammals.

ROOTS

By virtue of their genetic origin, root systems of trees tend to exhibit three morphological types: taproot, heartroot, and plate or flatroot (Fig. 3–1). A **taproot** consists of a nearly vertical main root and many laterals terminated in feeding roots; the feeding roots carry either root hairs or fungus-modified short roots, called mycorrhizae. A taproot system is particularly common to pine and oak species. Its full development is reached in permeable, adequately moist, but well-aerated soils. A **heartroot** lacks the main root but consists of several primary and secondary laterals, extending into a network of fibrous feeding roots. This root system pattern is produced by maple, beech, and fir. It attains its full development also in permeable, well-aerated soils. A **plate** or **flatroot** is composed of anchoring horizontals and numerous fringe roots. It is exhibited by spruce, hemlock, and other trees of saprophytic tendencies, especially when they grow in poorly drained soils (Hartmann, 1951).

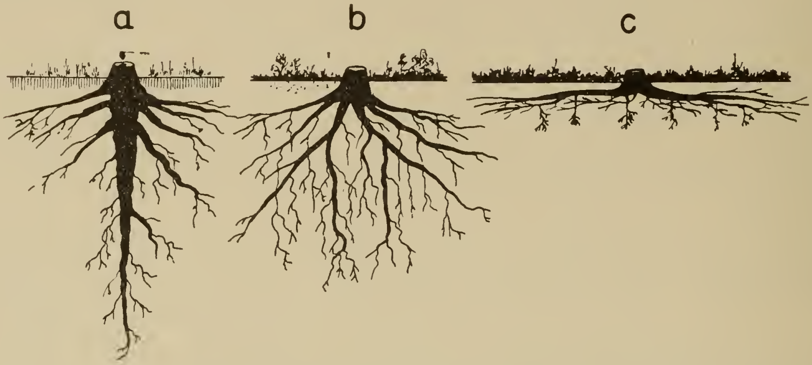


FIG. 3–1. Major types of root systems of forest trees: (*a*) taproot consisting of a main root and many laterals terminating in feeding roots with root hairs or mycorrhizae; (*b*) heartroot comprised of primary and secondary laterals extending into a net work of fibrous feeding roots; (*c*) plate-shaped or flatroot composed of anchoring horizontals and numerous fringe roots.

Under the influence of soil properties the root systems of all patterns undergo numerous modifications (Lutz *et al.*, 1937). In soils whose surface layers are subject to periodic droughts, the taproot and heartroot systems reduce their superficial laterals (Fig. 3–2*a*, *b*). A similar tendency is also common in soils with extended capillary fringe (Fig. 3–2*c*). In soil profiles intersected by a horizon of low water-holding capacity, the taproot conspicuously reflects the soil's moisture regime (Matiuk, 1953); it develops a crown of laterals near the soil surface and an abundant fibrous network in the deep layer of the soil (Fig. 3–2*d*). Soils underlain by dry substrata tend to develop either flattened heartroots or plate-shaped roots (Fig. 3–2*e*). Such roots are common in shallow outwash silt loams underlain by stratified gravel, in blankets of lacustrine clays deposited over sandbeds, and in dune sands.

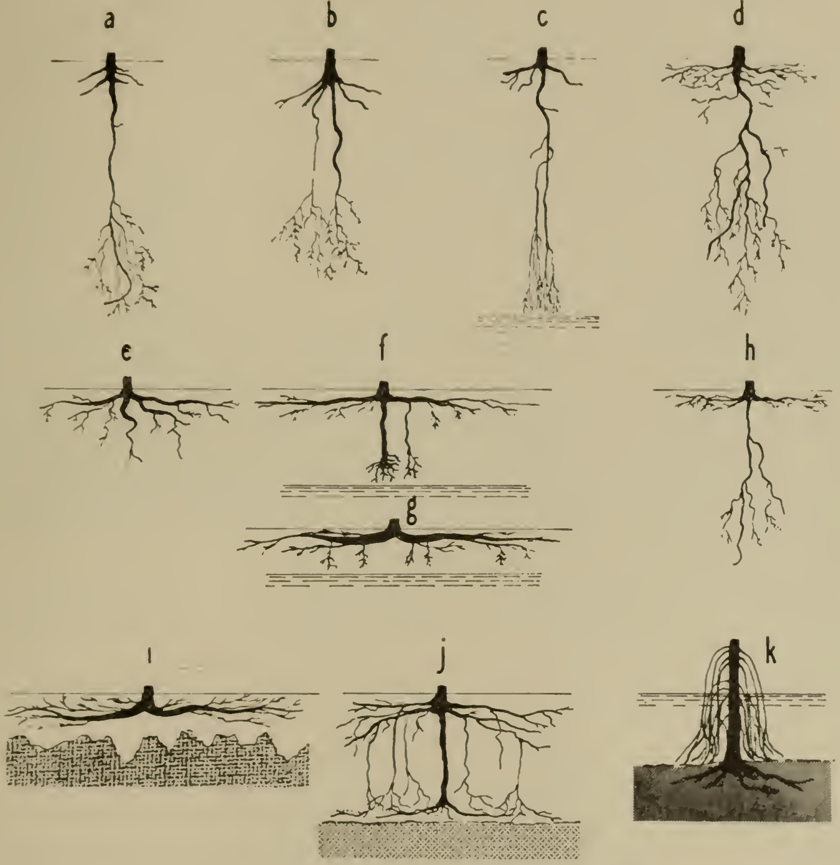


FIG. 3-2. Root systems modified by composition of soil profile and state of ground water table: (*a* and *b*) taproots and heartroots with reduced upper laterals, patterns encountered in coarse sandy soils underlain by fine-textured substrata; (*c*) taproot terminated by long tassels, a morphology induced by extended capillary fringe; (*d*) a collar of superficial laterals and a deep network of fibrous roots delineating the interlayer of porous material; (*e*) flattened heartroot formed in a lacustrine clay over a sand bed; (*f*) plate-shaped root developed in a soil with a reasonably deep ground water table; (*g*) plate-shaped root formed in organic soils with a shallow ground water table; (*h*) bimorphic system of plate-like crown and a heartroot or taproot, a pattern characteristic of leached soils whose surface is enriched in organic matter; (*i*) flatroot with organotropic secondary roots developed by hardwoods in strongly leached soils with raw humus; (*j*) two parallel plate roots connected by vertical joiners, a root system peculiar to hardpan podzols; (*k*) pneumatophors or "breathing roots" of mangrove trees inhabiting tidal lands.

Soils with a deep ground water table, especially those with a leached surface layer, are characterized by plate-shaped root systems of anchoring horizontals and long terminal tassels (Fig. 3–2*f*). Soils with a shallow ground water table, such as peat and muck soils, give rise to a superficial flatroot system with numerous aerotropic secondary roots (Fig. 3–2*g*).

A bimorphic pattern of roots is developed by soils covered with a substantial layer of raw organic remains and possessing a horizon with incorporated humus; a root system of this kind exhibits a near-surface collar of organotropic secondary roots and a deep tap- or heartroot (Fig. 3–2*h*). Strongly leached soils with a thick layer of raw humus tend to produce platelike roots of widely spread horizontals which at times carry upward-oriented organotropic secondary roots (Fig. 3–2*i*); this type of root—of a rather unusual morphology—is developed to the extreme by beech and hard maple growing on raw humus soils. Soils with a raw humus and a cemented hardpan horizon modify the taproot and heartroot systems into a pattern of two parallel plate roots connected by vertical joiners (Fig. 3–2*j*). A somewhat similar morphology of the root is molded by blackearth soils underlain by a zone enriched in calcium carbonate or gypsum. Permanently flooded soils of bayous and mangrove swamps produce peculiar pneumatophoric root systems extending above water level (Fig. 3–2*k*).

As soon as the rootlet enters the ground, its excretions attract or stimulate multiplication of soil microorganisms. The zone of microbe congregation in the immediate proximity of the root is called the **rhizosphere.** In many instances, members of the rhizosphere belonging to symbiotic bacteria, fungi, or actinomycetes penetrate the cortex tissues of the root and within a few weeks produce detectable swellings: **nodules** or **mycorrhizae** (Fig. 3–3). In other cases symbiotic fungi envelop the active portion of the root in a **mycoclena,** a mantle of mycelia. At times the roots are invaded by the hyphae of hostile damping-off or root-rot fungi which kill the trees.

Thus, the root invariably presents a center of microbiological activity and intricate nutritional, growth-promoting, antibiotic, and pathogenic relationships. Not all the details of these relationships are completely understood, but there is sufficient evidence to state that the inherent properties of the root, strength of its tissues in the early stages of development, and the composition of the rhizosphere are decisive for the nutrition, growth, and often survival of the plant. As Darwin once implied, correctly or otherwise, if the plant had a brain, it would lie in its roots.

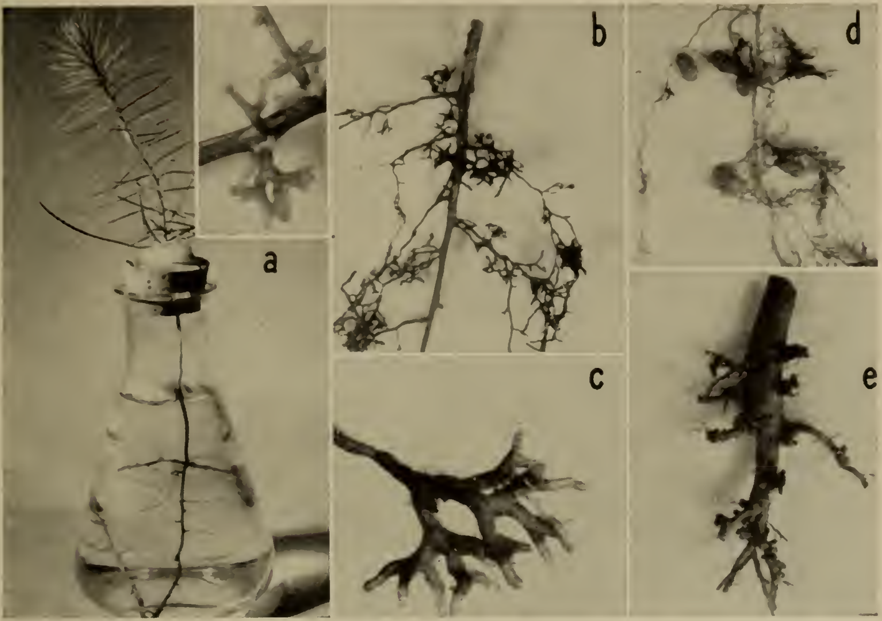


FIG. 3-3. Root systems of forest trees modified by symbiotic microorganisms: (*a*) forked short roots representing embryonic or "virgin" mycorrhizae developed in a nutrient solution, probably under the influence of growth-promoting substances emitted by common molds; (*b*) mycorrhizal short roots of Monterey pine; (*c*) enlarged cluster of mycorrhizae; (*d*) nodules of black locust produced by *Rhizobium* bacteria; (*e*) nodules of black alder produced by *Actinomycetes alni*. (After G. W. Wallis, 1957.)

With advanced growth the root begins to play an important part as a soil-forming agent. The physical entrance of roots compresses the soil and changes locally its porosity and bulk density. Upon decay, roots leave humus-filled spaces which serve as channels for the passage of water, air, and roots of the younger plants. In calcareous soils root systems consume carbonates and thus create a honeycomb of void spaces which give rise to the nutlike structure of soils—a feature especially prominent in the prairie-forest transitions.

The granulating and channeling action of roots is of considerable importance for silvicultural practice. Soils in which passages have been destroyed by a prolonged cultivation of field crops are not readily permeable by the roots of some commercially important forest trees. Scotch pine is a species of a tremendous resistance to drought and frost; yet it remains extremely shallow-rooted on old abandoned fields and is often damaged on such sites by the lack of summer or winter precipitation (Voigt, 1950). To correct this unfavorable condition of the old field soils, some European foresters go so far as to suggest the establishment of pioneer plantations of elderberries and other species whose roots have an ability to penetrate the channel-free soils.

Side by side with their tunneling and granulating work, roots bind the soil in a firm sinuous net which moderates the destructive action of water and wind erosion.

By excretion of carbonic acid, chelating effects, and rhizospheric concentration of microorganisms, the root systems increase the solubility of chemical compounds. This in turn promotes leaching of salts from the root-adjoining regions of the soil, and the paths of the old roots are often marked by the white or ash-gray tongues of bleached material.

Under the influence of percolating water, soils sometimes attain the stage of "senility," manifested by the development of an impervious subsurface layer, strong acidity, and exhaustion of the supply of nutrients. This condition, common under the forest cover of hemlock, spruce, and some other climax conifers, is accompanied by an arrested penetration of root systems and a decreased rate of the stand's growth. Fortunately enough, the everlasting existence of this type of climax forest and indurated soils is often precluded by the cyclic pattern of earthly processes. Sooner or later the shallow anchored stand is uprooted by wind, together with the depleted surface layers of the soil. Thus the root system performs its last duty with the help of the wind; acting as a soil cultivator, it rejuvenates the ground for a new crop of pioneer trees.

The magnitude and importance of all the effects of roots, especially their contribution to the content of soil organic matter, may be fully comprehended by the realization that the root system of a single white oak attains at times a total length of several hundred miles.

BACTERIA

With no exceptions the soils of forests harbor bacteria, which live on the roots of trees and lesser vegetation, in contact with soil particles, and in the soil solution. The number of bacteria per gram is estimated in hundreds of thousands in sands and in millions in fertile loams. Bacteria influence the processes of soil development and the growth of forest vegetation. They decompose organic remains and increase the availability of nutrients through oxidation, evolution of carbon dioxide, and symbiotic association. The fixation of atmospheric nitrogen is a process accomplished largely by bacteria. Sometimes bacteria render nutrients unavailable through the reduction of chemical compounds or the incorporation of salts into the tissues of their bodies. Both metabolism and absorption of salts by bacteria greatly aid the retention of plant food in the upper soil layers. The bacteria modify the mobility of soil colloids and promote the formation of soil aggregates.

The bacterial population of soils falls into two broad groups determined by the mode of nutrition: autotrophic and heterotrophic bacteria.

Autotrophic bacteria live without organic matter, utilizing elements or simple compounds for energy and deriving their body carbon from carbon dioxide. To this group belong nitrite-forming and nitrate-forming bacteria and bacteria oxidizing sulfur, iron, hydrogen, carbon monoxide, methane, and similar carbon compounds.

Heterotrophic bacteria feed chiefly on organic matter. To this group belong free and symbiotic nitrogen-fixing bacteria, bacteria-decomposing fats, proteins, cellulose, and other carbohydrates, and some denitrifying bacteria. A considerable portion of heterotrophic forms live in the absence of oxygen and are called **anaerobic**, in contrast to **aerobic** forms, which develop in the presence of air.

The outlined division is of great practical importance in the management of forest soils, particularly forest nursery soils. Organic matter is essential in the maintenance of soil fertility. The normal nutrition of trees can seldom proceed without participation of soil bacteria. Some of these bacteria live on organic residues, which they gradually destroy, while others not only prefer purely mineral substances but may even be injured by organic matter. Under natural conditions all of these seemingly paradoxical tendencies are in correlation (Winogradsky, 1938). However, unskilled application of organic matter and mineral fertilizers may easily destroy the existing equilibrium of bacteria and upset the nutrition of nursery stock. Therefore, the maintenance of soil microorganisms in a state of natural balance is one of the important problems of nursery soil management. A discussion of the nutritional effects produced by various groups of bacteria follows.

Carbohydrate-decomposing bacteria. Carbohydrates comprise a large portion of organic matter. They include sugars, starches, cellulose, and hemicelluloses. Cellulose is the most abundant constituent, and the process of its decomposition influences soil fertility.

The role of cellulose in plant nutrition is of a complex nature: it may exert either beneficial or harmful influences. Cellulose serves directly or indirectly as a source of energy for nitrogen-fixing bacteria and other useful organisms but has no value as a plant nutrient or base exchange material. In large quantities it encourages the growth of organisms utilizing ammonia and nitrates and, thus, may cause the nitrogen starvation of trees.

The cellulose-decomposing bacteria include both aerobic and anaerobic forms, such as *Cellulomonas,* certain *Spirochaetes* and *Clostridia.* In compost piles with a high temperature, these organisms may be partly replaced by thermophilic bacteria, *Clostridium thermocellum.* The mechanisms of cellulose decomposition vary, depending upon the conditions of environment and the organisms involved. However, the end products usually include carbon dioxide, methane, hydrogen, other gases, and bacterial cells mixed with decay-resistant substances.

The aerobic cellulose-decomposing bacteria are very intolerant of poor aeration and soil acidity. Their activity ceases completely at a reaction lower than pH 5.5. Consequently, they are confined chiefly to hardwood mull loams and weakly podzolized pine sands. The anaerobic bacteria withstand both strong acidity and deficiency of oxygen; they thrive on poorly drained and acid forest soils, in deposits of peat, and in overwatered compost piles.

Raw organic remains applied in forest nurseries as fertilizing material usually contain about 40 per cent carbon and 2 per cent nitrogen. When such remains are added to a nursery soil, cellulose-decomposing bacteria multiply rapidly, using for their cells both carbon and nitrogen. As the bacterial cells are composed approximately of one part nitrogen and five parts carbon, the supply of nitrogen present in both soil and organic remains may be soon exhausted. Unless the soil receives a new supply of nitrogen in the form of fertilizers, deficiency of this element will arrest the process of decomposition and bring about the starvation of nursery stock. Such consumption of nitrogenous compounds by cellulose-decomposing bacteria often takes place in composted fertilizers and should be prevented by applications of soluble nitrogen salts.

The decomposition of hemicelluloses and other carbohydrates is on the whole similar to that of cellulose, except that it proceeds more rapidly and plays a less important part in the state of soil fertility.

Protein-decomposing and ammonifying bacteria. The bulk of nitrogen in soil, forest litter, and organic fertilizers is the form of protein-like compounds. These cannot be utilized by trees directly and must first be broken down into amino acids, ammonia, and nitrates. The process of decomposition is accomplished by the combined action of chemical, enzymatic, and biological agents, particularly by aerobic and anaerobic bacteria, such as *Bacillus mycoides, B. putrificus, B. vulgare,* and *B. subtilis.* In some instances the chain of transformations is concluded by the formation of ammonia, which is released as a waste product of ammonifying bacteria. Under aerobic conditions, however, ammonia may be further transformed into nitrates by nitrifying bacteria.

Nitrifying bacteria. The transformation of ammonia nitrogen into nitrates is accomplished by two groups of aerobic bacteria. Some of these, belonging to the *Nitrosomonas* group, oxidize ammonia to nitrites, whereas others, e.g. *Nitrobacter,* oxidize the nitrites to nitrates.

Good aeration, adequate supply of water, fairly high temperature, presence of buffers, and the absence of large quantities of soluble organic matter or highly concentrated salts are essential for the process of nitrification. As a rule, nitrification is promoted by a reaction approaching neutrality, although some organisms specifically adapted to acid media produce nitrates in forest soils having a reaction as low as pH 4.8 (Hesselman, 1917).

The maintenance of soil in a condition suitable for the propagation of nitrifying bacteria is important chiefly in dealing with deciduous, lime-loving tree species, requiring nitrogen in the form of nitrates. On the other hand, certain deviations from the nitrification optimum may be tolerated in soils supporting stands or nursery stock of acidophilous conifers, because such trees readily utilize the nitrogen of ammonia and possibly that of amino acids.

Denitrifying bacteria. Under anaerobic conditions certain bacteria derive their oxygen supply from the oxides of nitrogen. In this process the nitrate is reduced by bacteria to nitrite and further to nitrous oxide or elemental nitrogen. The group of bacteria capable of denitrification includes hundreds of species greatly diversified in their other activities.

The reduction of nitrates to nitrites usually takes place in wet soils of a neutral or slightly alkaline reaction. In acid soils nitrates are likely to be reduced to ammonia with nitrites as an intermediate product. The adverse effects of denitrification are largely limited to stands of lowland hardwoods and nursery stock on heavy soils.

Nitrogen-fixing bacteria. Although an abundant supply of elemental nitrogen is always present in the atmosphere, it is not available to plants until it is converted into simple compounds. A small portion of this conversion is accomplished by electrical discharges;

the rest is brought about largely by the activity of nitrogen-fixing bacteria. Such bacteria exist either as free or symbiotic organisms. The latter develop nodules on plant roots and are commonly referred to as "nodule bacteria."

The free nitrogen-fixing organisms include aerobic *Azotobacter* and anaerobic *Clostridium.* Aerobic forms are extremely sensitive to the acidity of soil and other conditions, and their distribution is confined chiefly to well-aerated loam soils with reaction above pH 6.0. Consequently, these bacteria are of secondary importance in forest soils. The anaerobic forms occur nearly universally in soils, with the possible exception of acid peat bogs, and play a significant part in the growth of forest vegetation. A reaction not lower than pH 5.0, an adequate supply of organic matter, and a fairly high temperature are essential for the optimum activity of these organisms.

In the symbiotic fixation of nitrogen, leguminous plants provide bacteria with carbohydrates and in return receive nitrogen compounds. The nitrogen accumulated by nodule bacteria is likely to be directly available and is transferred to the plant at a rather constant rate.

The nodule bacteria, *Rhizobium,* are usually quite specific in their requirements. They can withstand about the same pH as their respective hosts. The forms associated with soybeans, lupines, and some vetches can survive at pH 4.0, thus permitting their advantageous use in forest nurseries. In spite of the great tolerance of certain legume bacteria to acidity, the rate of nitrogen fixation is usually increased by the addition of lime. Mineral fertilizers and organic remains are also indirectly effective, owing to increased growth of the host plant. In the great majority of cases inoculation of seeds with the proper culture of bacteria is necessary to obtain satisfactory results with leguminous green manure crops.

Some forest trees, such as black locust, are also benefited in their nitrogen nutrition by *Rhizobium* spp. and may require artificial inoculation. Although these bacteria are often present in nursery soils, their viability is greatly influenced by pH, organic matter, moisture, temperature, and toxic agents. Consequently, it is advisable to inoculate seed with a known effective strain rather than to depend upon the presence of the organism in the soil (Fred, Baldwin, and McCoy, 1932).

Like many other bacteria, the members of the *Rhizobium* genus radically change their morphology in the course of their life cycle and under the influence of environmental conditions (Fig. 3–4).

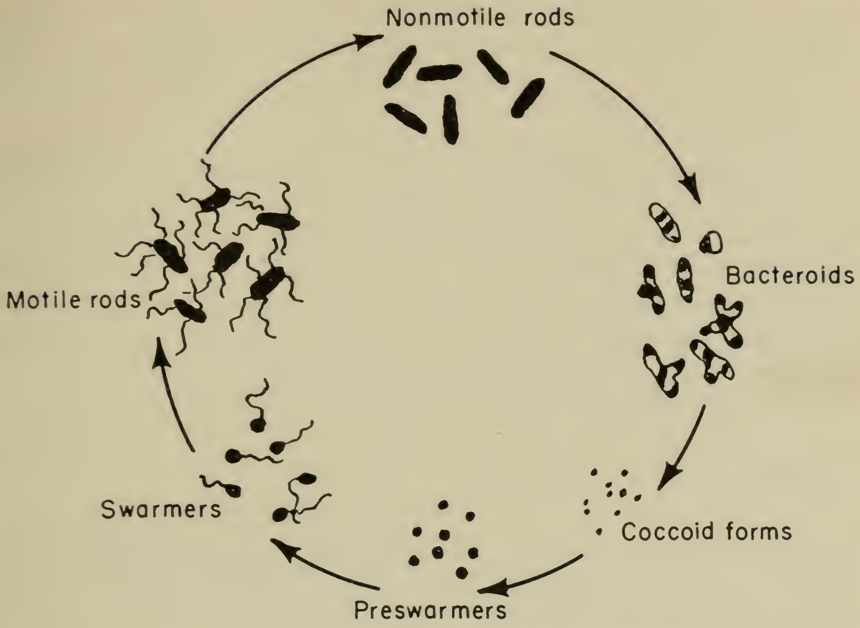


FIG. 3-4. Changes in morphology of *Bacillus radicicola* (*Rhizobium* genus) during its life cycle. (After Thornton and Gangulee.)

Sulfur bacteria. From the standpoint of nutrition sulfur is closely related to nitrogen and undergoes similar biological transformations. The oxidation of elemental sulfur and sulfides into available sulfates and sulfuric acid is accomplished primarily by a specific group of sulfur bacteria, including *Thiobacillus, Beggiatoa,* and *Thiothrix.*

Because the acidification of nursery soils supporting coniferous stock is often desired, the sulfur-oxidizing bacteria attain a considerable importance in forestry practice. The activity of these organisms is stimulated by additions of flowers of sulfur and various organic remains, such as green manure, peat, raw humus, or compost. The oxidation of sulfur may be advantageously used in the preparation of composted fertilizers, because the sulfuric acid converts the insoluble rock phosphates into monocalcium phosphate, a compound readily available to plants.

The reduction of sulfates or other sulfur oxides to hydrogen sulfide is similar in its nature to denitrification and is accomplished by a wide variety of both autotrophic and heterotrophic organisms capable of carrying on anaerobic respiration. *Sporovibrio desulfuricans,* a strictly anaerobic spirillum, plays an outstanding part in this transformation. The reduction of sulfates takes place prevailingly in poorly drained soils, especially peat and muck. The accumulated hydrogen sulfide exerts a toxic effect upon the roots of the trees and may be partially responsible for poor growth of trees in stagnant swamps.

Iron bacteria. A number of bacterial forms, such as *Crenothrix, Leptothrix,* and *Gallionella,* derive their energy from the oxidation of ferrous iron, thereby converting it into the slowly soluble ferric precipitate. This process plays a certain part in the development of iron-rich horizons of forest soils. Aside from the activity of the iron bacteria proper, a number of other bacteria may cause development of a hardpan or bog ore by using the organic fraction of soluble iron humates and leaving iron hydroxide as a residue.

FUNGI

Fungi are multicellular, chlorophyll-free thallose plants which derive their energy from decomposition of dead or living organic matter. Taxonomically, soil-inhabiting fungi are classified into five broad classes: Myxomycetes, or slime molds, forming a transition between plants and animals; Phycomycetes, alga-like fungi, including "black molds" and genera causing damping-off disease, for example *Pythium* and *Phytophthora*; Ascomycetes, sac fungi, represented by yeasts, blue and green molds, such as *Penicillium* and *Aspergillus,* and delicious morels and truffles; Basidiomycetes, including rusts, smuts, mushrooms, toadstools, and puffballs; Fungi Imperfecti, embracing many genera of obscure life history and problematic taxonomic position (Christensen, 1951).

Fungi are much less specific in their functions than bacteria, and their toxonomic classification is not of great direct value to a student of soils. For this reason the morphological subdivision of fungi is often supplanted by a classification on an ecological or functional basis (Waksman, 1952). Depending upon the mode of nutrition, the fungi fall into three major divisions: saprophytic, parasitic, and symbiotic or mycorrhizal fungi.

Saprophytic fungi. The role of these organisms in forest soils cannot be overemphasized. In all probability there is no leaf or needle on the floor of the world's forest whose decomposition is not at least in part accomplished by fungus mycelia. Fungi decompose proteins, cellulose, other carbohydrates, and lignin. They tolerate strong acidity and mild alkalinity, and they survive periodic droughts; but the deficiency of air often restricts their entrance into the deeper soil layers. Aside from this the distribution of fungi is limited by their deadly enemies, the arthropods which feed on mycelia and spores (Forsslund, 1945).

Under favorable conditions the activity of fungi proceeds very efficiently with comparatively little consumption of energy material and climaxes in the accumulation of a highly nitrogenous residue of mycelia. The subsequent breakdown of mycelia, as well as the release of ammonia as a waste product of the fungal metabolism, enriches the soil in available nitrogen. In a cold and humid environment, however, fungus hyphae may resist decomposition and contribute to the development of a thick layer of inert raw humus. In this way fungi may immobilize soluble nitrogen and other elements and may virtually deplete the supply of available nutrients.

Fungi may modify the reaction of soil by the liberation or consumption of organic acids and by the formation of ammonia. In some instances they increase the availability of phosphates and other nutrients by evolving carbon dioxide.

The ability of fungi to decompose sawdust, wood chips, and other organic remains, and their effect upon the solubility of mineral compounds are finding constantly increasing use in the preparation of artificial organic manures and composted fertilizers (Waksman, 1952; Davey, 1952).

As recent investigations have shown (Tresner *et al.*, 1954), the occurrence of many soil-inhabiting saprophytic fungi is closely correlated with the nature of soil and the distribution of trees and ground-cover vegetation.

Parasitic fungi. Some of the fungi do not draw an exact line between the dead and the living organic matter and cause the destruction of tissue of seedlings and older trees. The members of *Rhizoctonia, Pythium, Phytophthora,* and other genera attack forest seedlings before or shortly after germination and thus cause either pre-emergence or post-emergence damping-off. This disease is frequently responsible for great losses of nursery stock (Boyce, 1948; Baxter, 1952). Occasionally damping-off fungi act as a factor limiting the distribution of certain tree species, particularly conifers (Wilde and White, 1939). In close relation to damping-off fungi are species of *Fusarium* and other root-rot fungi which cause the decay of transplants and seedlings in advanced stages of their development. Among the fungi invading the roots of older trees, members of the Polyporaceae, especially *Fomes* spp., *Armillaria mellea*, *Verticillium rhizophagum*, *Phymatotrichum omnivorum*, and *Endoconidiophora fagacearum* are a few that could be mentioned.

Mycorrhizal fungi. A great number of fungi exist in symbiosis with trees and other higher plants. The mycelium of such fungi enters or envelops the roots and at times causes certain modifications in the live tissues; the resulting new "fungus-root" organs are referred to as **mycorrhizae.** This morphological alteration has profound physiological consequences; it permits mutually beneficial exchange of soluble carbohydrates, nutrients, and perhaps growth-promoting substances between the higher and the lower plants. As the result of this symbiotic association, trees attain an increased vigor and rate of growth (Fig. 3–5).

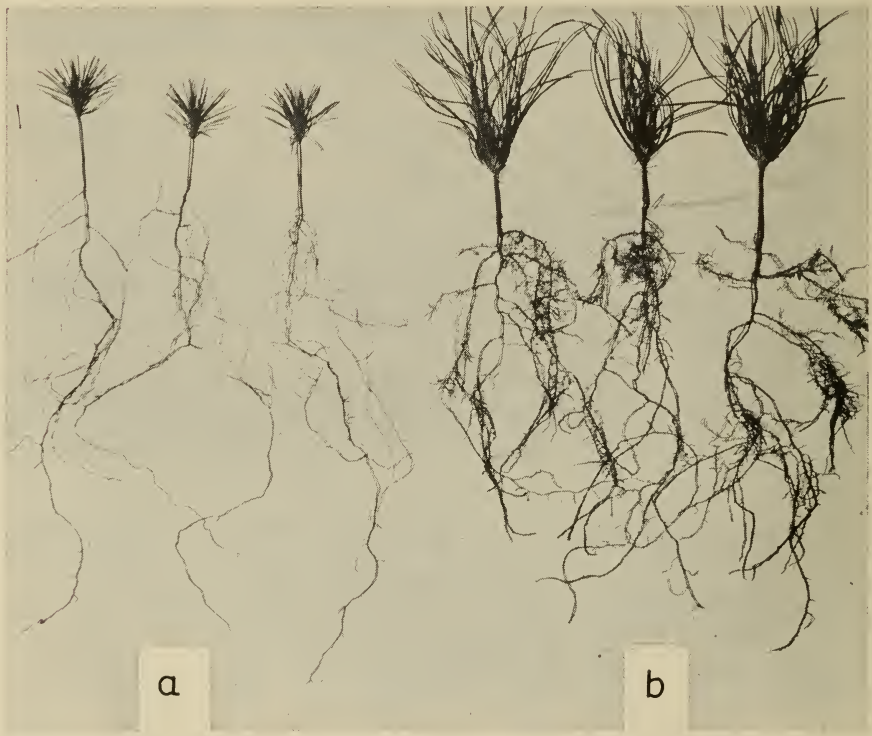


FIG. 3-5. Effect of mycorrhizal fungi on the growth of tree seedlings: (*a*) one-year-old red pine raised in a virgin prairie silt loam; (*b*) red pine of the same age and origin raised in a similar soil inoculated with *Boletus felleus.* (After R. O. Rosendahl, 1943.)

Depending upon the position of the fungus in relation to the roots of the host, mycorrhizae are classified as ectotrophic, endotrophic, or peritrophic.

Ectotrophic mycorrhiza is characterized by simple or branched nodule-like swellings, called "short roots" (Fig. 3–6). These are detectable by ocular examination and consist of the modified root tissues enveloped and penetrated by fungus mycelia. Within the short root the mycelial hyphae are confined to the intercellular spaces and enwrap each cell of the cortex into their mesh, called **Hartig net.** In a cross section the Hartig net appears like a projection of a fence surrounding individual cells. Observations in artificial cultures indicate that the development of ectotrophic mycorrhiza is initiated by the transformation of a normal root hair into simple or branched swellings. This alteration is likely to be effected by growth-promoting substances emitted by mycorrhizal or other fungi surrounding the root. At a later date the mycelia-free "virgin" short roots are gradually enveloped and penetrated by fungal hyphae. Ectotrophic mycorrhizae occur on both coniferous and deciduous species, particularly pine, spruce, fir, larch, hemlock, beech, oak, chestnut, hornbeam, and hazelnut.

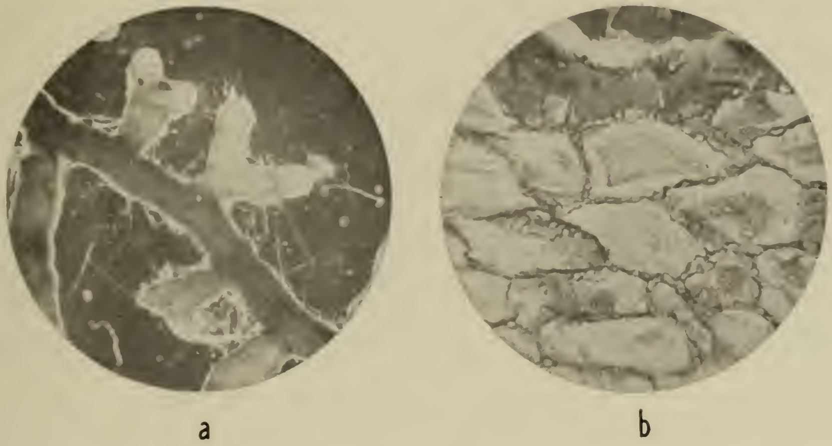


FIG. 3-6. Ectotrophic mycorrhiza of pine seedlings: (*a*) fully developed short roots in the middle of the growing season; (*b*) cross section of a short root showing "Hartig net," the intercellular penetration of the cortex tissue by mycelia.

Endotrophic mycorrhiza is formed by the mycelium developing within the cells. Upon entrance into the epidermal and cortical cells, hyphae form peculiar shapes: **vesicles** or bladder-like organs and **arbuscules** or cauliflower-like organs. These vesicular-arbuscular mycorrhizae are formed in cypress, cedar, yew, sycamore, walnut, ash, some poplars, citrus, and many other fruit trees, tea, coffee, and rubber; they are best known as symbionts of orchids and heath plants. In some cases, the roots may carry combined **ectendotrophic mycorrhizae** (Björkman, 1949).

The **peritrophic mycorrhiza** is a condition in which the mycelium envelops the root as a superficial sheath or "mycoclena" but does not penetrate cortical tissues (Peyronel, 1922; Jahn, 1934). This type of union between the root and the fungus is a striking example of the broader relationship—**rhizospheric symbiosis** (Hiltner, 1896; Kürbis, 1937). Peritrophic mycorrhizae are formed on all trees and shrubs whenever the conditions prevent the penetration of cortical cells by mycelia.

In either form of the root-fungus association, the fungi connect the higher plants with a large volume of the soil through their extensive external mycelia. The spread of such mycelia is frequently indicated by "fairy rings" of mushrooms, enclosing an area of several hundreds of square feet.

Existing evidence suggests that mycorrhizae of forest trees are formed chiefly by Hymenomycetes, such as *Boletus, Amanita, Tricholoma, Boletinus, Lactarius, Cortinarius, Russula,* and *Agaricus* (Hatch, 1937; Hacskaylo, 1951). In some cases members of Fungi Imperfecti, for example *Cenococcum graniforme,* produce mycorrhizae (Mikola, 1948; Levisohn, 1957). Phycomycetes of the genus *Rhizophagus* appear to be common formers of the endotrophic mycorrhizae. Truffles and fungi of many other taxonomic units are rated among the mycorrhiza formers of forest trees, largely because their sporophores were found to be connected with the root system. This, however, cannot serve as proof of a mycorrhizal relationship. The verification of the symbiotic association unfortunately is often precluded by the difficulties of raising mycorrhizal fungi in artificial cultures.

It was suggested that under certain conditions true mycorrhizae are replaced by harmful "pseudo-mycorrhizae," produced by *Mucor, Verticillium,* and other common fungi (Melin, 1925). Such a replacement is usually restricted in scope and does not interfere with metabolic processes of trees or lead to the deterioration of root systems (Harley, 1948).

A long period of studies gradually revealed that mycorrhizal fungi supply higher plants with nitrogen, potassium, phosphorus, and other nutrients which they extract from raw organic remains and unweathered minerals (Frank, 1885; Stahl, 1900; Falck, 1923; Rosendahl, 1942; Stone, 1950). The utilization of nutrients locked in peat, raw humus, lignoproteinates, feldspathic minerals, apatite, or limestone is facilitated by the high dissolving ability of fungus bodies and the large absorbing surface of fungus mycelia. This effect of mycorrhizae in increasing the availability of nutrients is of considerable practical importance; it appreciably reduces the expenses for commercial fertilizer in nurseries and arboricultural plantations. The use of less-soluble sources of potash and phosphates may prove to be not only cheaper, but also a safer means of fertility maintenance of soils supporting mycorrhizal plants (Fig. 3–7).

It was suggested as early as 1899 by Ward that "one symbiont may stimulate another by excreting some body which acts as an exciting drug to the latter." At present there is evidence that the fungus is dependent upon the higher plants for its supply of thiamin and other vitamins.

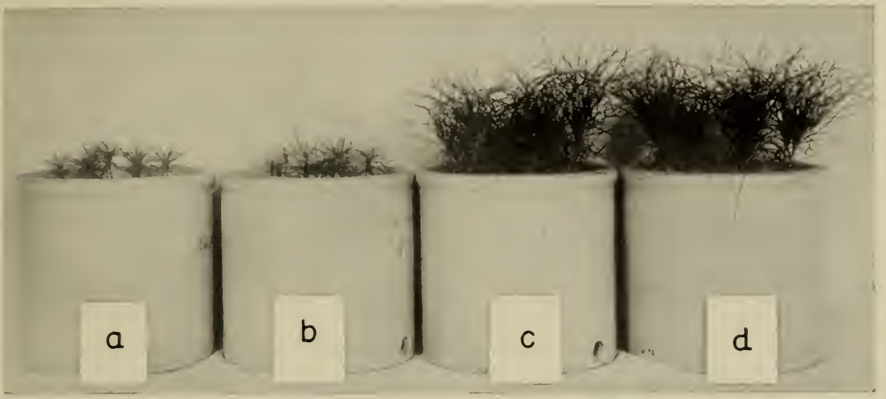


FIG. 3–7. Effect of mycorrhizal fungi on utilization of potassium in the form of slowly soluble feldspar. (*a* and *b*) Quartz sand cultures with a complete nutrient solution except for potassium, which is added as 60-mesh orthoclase at the rate equivalent to 3 tons per acre. (*c* and *d*) Similar cultures inoculated with *Boletus felleus*. (After R. O. Rosendahl, 1943.)

The abundance of mycorrhizal short roots and intracellular mycelia shows a close correlation with the state of soil fertility. It is likely that the development of either ectotrophic or endotrophic mycorrhizae is controlled by the concentration and balance of nutrients within the host plant and by the ability of root tissues to resist the penetration of mycelia. As a rule, the prolific development of mycorrhizae coincides with a deficiency or an excess of certain nutrients. The overfertilized and extremely succulent hydroponic stock shows superabundant, almost "pathological" development of mycorrhizae shortly after being transplanted into a forest soil. Similar behavior is exhibited by artificially rooted twigs or cuttings of conifers.

The proof of the practical importance of mycorrhizae was obtained by silviculturists operating in the regions of prairie or other grassland soils which have not previously supported forest cover. Observations of these specialists established with certainty that grassland soils do not harbor mycorrhizal fungi and that the absence of these organisms impedes the normal development of tree seedlings (Wissotzky, 1902; Hatch, 1937). Recent investigations have suggested that the survival of mycorrhizal fungi without their woody symbionts is precluded in grassland soils by toxic or antibiotic substances emitted by roots of prairie plants (Curtis and Cottam, 1950).

In many instances the inoculation of seedbeds by the addition of forest soil or by planting mycorrhiza-infested seedlings saved from abandonment nurseries established on grassland soils, as reported by Clements (1938) and McComb (1938). The study by White (1941) suggested that the very existence of the intrazonal prairies in North America is related to the absence of mycorrhizal fungi. Convincing evidence of the beneficial effect of mycorrhizae has been obtained by Melin (1917) with soils of entirely different nature—drained peats of Sweden. In such soils the seedlings lacking mycorrhizae showed symptoms of nitrogen starvation and eventually died, while seedlings infected with mycorrhizal fungi grew successfully.

In spite of the unquestionable importance of the symbiotic relationship in the life of forest vegetation, many details in the behavior of mycorrhizal organisms have been grossly exaggerated. The claims that mycorrhizal fungi disappear from soils with the removal of trees and must be introduced artificially for direct reseeding of old cutover areas have been definitely disproved (Rosendahl and Wilde, 1942). Results obtained with planting sterilized seed of several coniferous and deciduous species in soils of old abandoned fields gave rise to the credo: "Once forest soil, always forest soil." Extermination of symbionts in forest soils results only from radical changes of environmental conditions, such as those caused by severe fires of peat deposits, prolonged impoundment of water by beaver dams, and heavy applications of certain fungicides and insecticides (Wilde, Youngberg, and Hovind, 1950; Persidsky and Wilde, 1955; Simkover and Shenefelt, 1952). If reforestation or afforestation is accomplished by the use of nursery stock, inoculation of soils with mycorrhizal fungi has no justification, because all normally developed nursery seedlings invariably carry symbiotic organisms on their root systems. Therefore, the need for artificial introduction of mycorrhizal fungi is confined to the rare instances when establishment of forest cover on grassland or other mycorrhizae-free soils is attempted by the use of seed, hydroponic stock, or aseptically rooted cuttings (Wilde, 1954).

According to present evidence heavy applications of biocides suppress the development of normal ectotrophic or endotrophic mycorrhizae of nursery stock but do not necessarily exterminate symbiotic organisms. Therefore, the re-establishment of the productive capacity of biocide-treated nursery soils lies first of all in the elimination of toxic conditions and adjustment of soil fertility. In the great majority of cases these measures will recover the normal activity of symbiotic fungi and thus eliminate the need for soil inoculation.

Assertions of the specificity of mycorrhizal fungi and their higher site requirements in comparison with their tree symbionts, presumably leading to the failure of planted trees (Romell, 1939), have not been substantiated by observations.

ACTINOMYCETES

Actinomycetes are generally classed as fungi, although they exhibit characteristics of both fungi and bacteria. The body of these organisms consists of mycelia with branching nonseptate hyphae similar to those of higher fungi. The mycelium is brightly colored and is easily broken into short rods resembling bacteria. Most species produce a typical earthy odor of fresh soil.

In contrast with fungi, actinomycetes are very sensitive to acidity and disappear almost completely in soils having a reaction of pH 4.7 or lower. The absence of these organisms in strongly acid soils may have a bearing on the development of the highly ligneous layers of raw humus. Some actinomycetes have the ability to reduce nitrates to nitrites and may be detrimental.

The most outstanding characteristic of actinomycetes is their ability to produce antibiotics of high toxicity to other organisms including pathogens (Waksman, 1952).

One member of this group of organisms, *Actinomyces alni*, forms nodules on the roots of alder; this symbiotic union permits fixation of atmospheric nitrogen (Virtanen and Saastamoinen, 1933).

ALGAE

Algae are chlorophyll-bearing organisms generally occurring in filaments or colonies. The algal flora of the soil is confined to three groups: Cyanophyceae or blue-green algae; Chlorophyceae or green algae; and Bacillariaceae or rod-shaped diatoms.

Algae hasten the solubility of minerals, particularly carbonates, and thus aid in processes of weathering. Being capable of photosynthesis, they utilize carbon dioxide and increase the content of soil organic matter. Lichens, which are a symbiotic association of algae and fungi, are of great importance in initiating plant succession and development of soil on unweathered rocks and other barren parent materials. Some blue-green algae are capable of utilizing atmospheric nitrogen. It is possible that the growth of higher plants on poorly drained soils is benefited by the oxygen given off by the algae.

PROTOZOA

Protozoa are one-celled animals, varying in size from a few microns to several millimeters. Their protoplasm is either naked or enclosed in a membrane and carries one or more nuclei. Protozoa participate in the decomposition of organic remains and destroy certain parasitic as well as useful organisms. It was believed in the past that protozoa decrease the fertility of soils, or even cause a so-called

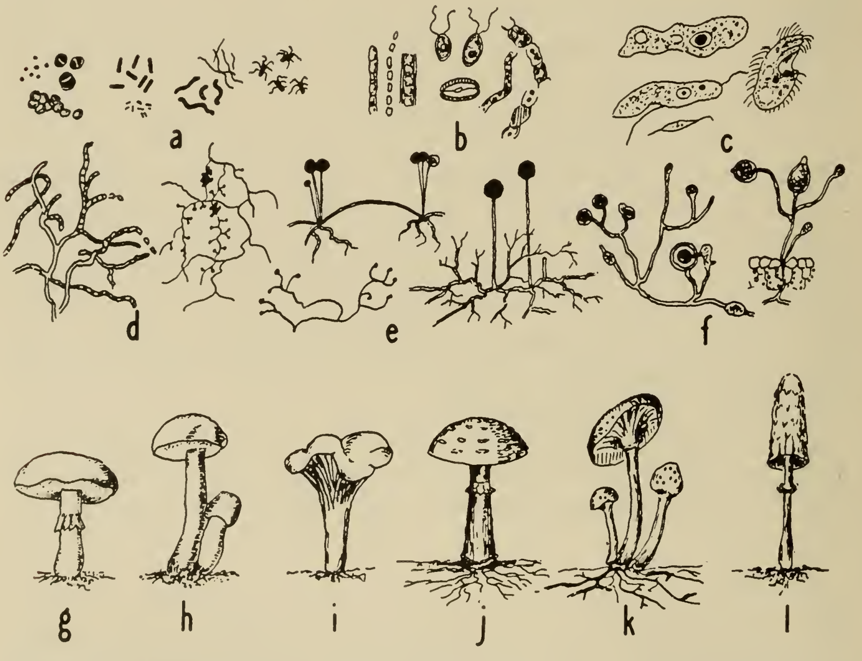


Fig. 3–8. Microorganisms inhabiting forest soils: (*a*) bacteria of different morphology—spherical cocci, rod-shaped bacilli, curved spirilla, and motile bacilli with flagella; (*b*) algae—filamentous colonies and diatoms; (*c*) protozoa—rhizopod or amoeba, ciliate and flagellate; (*d*) actinomycetes; (*e*) saprophytic molds; (*f*) parasitic fungi, causing damping-off disease. Fruiting bodies of some important soil fungi: (*g*) *Boletus luteus,* oily mushroom, mycorrhizal symbiont of jack pine, red pine, and their European cousin, Scotch pine; (*h*) *Boletus rufus,* delicious mycorrhiza-former of both American and European aspen; (*i*) *Cantharellus sibarius,* another edible mycorrhizal fungus; (*j*) *Amanita muscaria,* poisonous mycorrhiza-former; (*k*) *Armillaria mellea,* black shoestring fungus, tasty mushroom of parasitic tendencies; (*l*) *Coprinus comatus,* inky-cap mushroom, an efficient cellulose decomposer.

"soil sickness," by feeding on ammonia- and nitrate-forming bacteria. It was assumed that protozoa are less resistant to heat than bacteria, and a method of partial sterilization was advanced as a means of increasing soil fertility. The results of later detailed investigations, however, failed to support the soundness of these assumptions (Waksman, 1952). The use of partial sterilization in nursery practice is extremely dangerous because the elimination of some organisms may unleash the multiplication of damping-off fungi. Partial sterilization may also increase the content of ammonia and nitrites and suppress oxidation to nitrate, thus poisoning the plants. Injury by soluble manganese may also be expected as a result of this treatment (Russell, 1950).

Figure 3–8 illustrates some microorganisms inhabiting forest soils.

WORMS

Soil-inhabiting worms include two principal groups: Annelidae, the ringed or segmented worms, and Nematoda, the nonsegmented or round worms.

Ringed worms are the most highly developed form of worms. Their bodies consist of partitioned segments each of which has a separate nervous system. Their digestive mechanism is not dissimilar to that of the higher animals.

Ringed worms have numerous, not easily identifiable genera and species. Because of this, in investigations of forest soils they are classified into two broad divisions. All large and medium-size worms are rated as Lumbricidae, or, in common terms, as "night-crawlers," "fishworms," and "earthworms." All small, light-colored worms are considered Enchytraeidae or "potworms" (Shiperovich, 1936). This violation of scientific taxonomy is of no significance for silvicultural practice because the soil-forming effects of ringed worms can rarely be attributed to any one genus or species of either group of these animals.

Earthworms feed on fallen leaves and use them as litter in their burrows, thereby reducing or preventing the accumulation of raw organic remains on the soil surface. Even at a low density of three worms per square foot, these animals may rework as much as half a ton of leaves per acre per season. In the process of nutrition the worms pass great quantities of soil and organic debris through their bodies, thereby promoting humification and the incorporation of humus with mineral soil. A certain fraction of aggregated excrements is deposited by worms on the soil surface at a rate that may approach a quarter-inch per year. As the result of these activities of the worms, the upper layer of soil attains a typical crumbly structure of "earthworm mull," a characteristic type of humus in certain forest soils.

The spectacular soil-cultivating activity of worms received the attention of many scientists, including Charles Darwin (1881). Under certain conditions of climate, soil, and vegetation, the worms rejuvenate the soil and increase its porosity, aeration, and infiltration capacity; they facilitate the penetration of the roots of trees to a depth which in exceptional cases may reach 25 feet. However, these beneficial effects of earthworms are not always synonymous with a high level of forest soil productivity.

The distribution of most worms is limited by several factors, especially by the moisture content and reaction of the soil. The worms breathe through the entire slimy surface of their bodies, a process which becomes arrested as soon as their skin dries out. This physiological detail confines the worms to soils possessing an adequate supply of water, particularly to the fine-textured soils underlain by ground water. As found by Arrhenius (1926) and later Bornebusch (1930), earthworms avoid soils of strongly acid reaction. Furthermore, the existence of these animals depends upon the presence in the soil of a rather high content of available nutrients and organic matter. All in all, the requirements of worms often exceed the conditions offered by forest cover supported by sandy and strongly acid soils low in soluble salts.

The enormous area of forest soils affected by podzolization and laterization supports rapidly growing forest stands in complete absence of earthworms. The productive capacity of such soils is often expressed by yields exceeding 100 Mbf per acre. On the other hand, a considerable portion of forest soils, harboring a high population of earthworms, supports inferior or even struggling stands. The stands of oak and other deciduous species in the entire southern part of the Lake States region offer a striking illustration of this condition. The productive capacity of such stands seldom exceeds 10 Mbf per acre of second grade lumber and often declines to a few cords of fuel wood. Thus the textbook dithyrambs to the earthworms may be applicable to certain environments, particularly that of central Europe, but are without foundation in regard to many other forest regions.

The enchytraeids and other small white worms have considerably lower environmental requirements than their bigger cousins and in many instances are found in acid forest soils. Their activity is essentially similar to that of the large worms, except that it is restricted to the surface horizons. Under certain conditions enchytraeids may be of a greater silvicultural importance than the earthworms.

An account of the detrimental effects of worms encounters difficulty because such effects thus far have escaped the attention of soil students. It is known for certain that earthworms are responsible for the destruction of natural forest reproduction, especially that of conifers (Shiperovich, *op. cit.*). Consequently, they may act as one of the factors hindering the conversion of deciduous forest into coniferous stands. The beneficial role of the earthworms may be even more questionable in agricultural than in forest soils. According to Bornebusch (1930), the weight of worms per acre is at times equal to the weight of livestock on a well-stocked Danish farm. The maintenance of such a population of hungry underground dwellers obviously requires a large amount of raw organic tissues. Such can be provided by a forest stand but not necessarily by the land under farm management, and as concluded by Jacks (1954): "The farmer should remember that his prime job is to produce crops, not worms."

Nematodes, called roundworms or threadworms, are nonsegmented, spindle-shaped, often transparent worms of a microscopic or nearly microscopic size. They occur in the humus horizons of forest soils, being especially numerous in soils underlain by ground water. However, the ability of the eggs, as well as of the worms, to preserve life for several years in completely dry media permits the existence of nematodes also in coarse, sandy soils exposed to periodic drought.

Soil-inhabiting roundworms include saprophagous species, living on organic remains, and predatory species, devouring bacteria, protozoa, fungi, small arthropods, and other nematodes. The activity of nematodes contributes to the processes of humification and serves to improve the aeration and infiltration capacity of the soil. By distributing parasitic fungi, nematodes may increase the extent of damping-off or root-rot diseases. Some of the species, particularly *Rhabditis,* invade the tissue of live seedlings, producing the same effect as a damping-off fungi (Hansson, 1936; Wilde, 1936).

Soils of forests also harbor nematodes parasitizing on insects, birds, and quadrupeds. Many of them serve as natural control agents and are highly beneficial; they kill or castrate June bugs, bark beetles, and other injurious insects by invading their sexual organs. Other parasitic nematodes are extremely harmful and lead to serious functional disorders or death of birds and mammals. After heavy rains parasitic nematodes, Merithidae, collect at night on the soil surface in large numbers, a habit which gave rise to the early belief that "it rains worms."

ARTHROPODS

This broad division embraces animals with articulated body and limbs, such as insects, arachnids, and crustaceans. In spite of the considerable artificiality of the taxonomic classification, most of the members of the phylum Arthropoda are united in an ecological sense. Forest litter presents the common meeting ground for beetles and flies, their larvae, springtails, bristletails, ants, centipedes, millipedes, sow bugs, spiders, ticks, and mites (Kühnelt, 1950). The activity of these minute or large, slow-moving or swift, saprophagous or parasitic, but always efficient creatures is of unparalleled importance in the process of forest litter decomposition. Because many members of the arthropod group, particularly mites, escape man's vision, the humus-forming role of these animals often is overlooked (Eaton and Chandler, 1942).

Mites of primary pedological importance include the gnawing nonparasitic members of the *Acarina* order, particularly the members of the *Oribatidae* family. These microscopic or nearly microscopic spider-like animals occur in immense numbers in the surface layers of forest soils, sometimes exceeding several thousand specimens per square foot. As a rule, they constitute a large fraction of all soil inhabitants and are considered to be the most important soil organisms of the Arthropoda phylum.

Mites are particularly common in podzolic soils formed under the cover of raw organic remains. They consume both forest litter and fungus mycelia (Forsslund, 1945) and in numerous instances play the major part in the maintenance of the branlike structure and the small thickness of the superficial organic layer. In this manner, mites with the help of other organisms produce thin layers of "bran mor" or "superficial mull." Within the zone of hardwood-coniferous forests, such layers often overlay the ash-gray horizons of podzolized soils supporting stands with a predominance of spruce, hemlock, and other conifers.

Myriapods are insect-like animals with elongated bodies of many equal-size segments. The two distinct forms of this group are the centipedes and millipedes.

Centipedes carry one pair of legs on each of their segments. They are predators, devouring insects, snails, and worms. Millipedes have two pairs of legs on each segment and feed on dead organic matter, live roots, and seeds. They are largely confined to soils with mull humus layers, especially those supporting stands of deciduous trees.

The number of millipedes may be as high as half a dozen specimens per square foot (Kevan, 1955).

False scorpions are nearly microscopic predators resembling either crayfish or pincer-armed spiders. They are the tigers of the forest floor, hiding under the bark of the trees or in the jungle of moss cover, preying on insects, mites, and myriapods often many times their size.

Insects of importance in the life of the soil include beetles, flies, moths, springtails, bristletails, ants, and termites. Both saprophagous and predatory insects influence the composition of soils by their tunneling activity, breakdown of organic remains, and deposition of feces and chitinous exoskeletons.

The most abundant insects of forest soils are the diminutive wingless springtails. Their diet of dead tissues is often supplemented by nematodes. The humification activity of the springtails is often supported by their morphological relatives—bristletails.

A spectacular though not always beneficial influence is exerted by ants, whose building activity and "Times Square" traffic radically alters the relief of forest ground and obliterates horizons of the soil profile. Unfortunately, the excretion of formic acid and other substances at times leads to a deterioration of trees at a considerable distance from the ant hills. To a certain extent this adverse influence is balanced by the destruction of other harmful insects which are devoured by a single community of ants, *Formica rufa,* in numbers exceeding one hundred thousand specimens in the course of a day. In some forests of Germany, ant colonies are distributed artificially as a means of parasite control.

In tropical forests termites act as a particularly outstanding soil-forming factor by decomposing vast amounts of dead and living plants and by greatly increasing the soil porosity with their numerous passages.

Among the soil-inhabitating injurious insects, the white grub, wireworms, cutworms, and root-borers are of greatest importance. The first two destroy the roots of seedlings and transplants, whereas the latter cut the stems of young plants near the ground and feed upon the exuding sap.

Crustaceans which make their home in forest debris are confined to isopods, the small sessile-eyed creatures characterized by a body of seven free segments, each bearing a pair of legs alike in size and direction. The sow bugs and pill bugs of this group feed on deadwood, litter, and presumably fresh leaves (Lutz and Chandler, 1946).

The crayfish is one of the crustaceans whose limited distribution is confined to poorly drained soils of the temperate rainforest. The numerous passages of these animals appear to be instrumental in improving the drainage and aeration of soils to a considerable depth (Shaler, 1891).

In Danish forests, Bornebusch (1930) estimated, mull soils under beech stands harbor twenty-five million specimens of small soil-inhabiting animals weighing 630 pounds per acre and consuming 0.33 liter of oxygen per square meter per day; raw humus soils under beech stands were found to harbor fifty-seven million specimens weighing 214 pounds per acre and consuming 0.20 liter of oxygen per square meter per day.

Representative members of the forest soil fauna are shown in Figure 3–9.

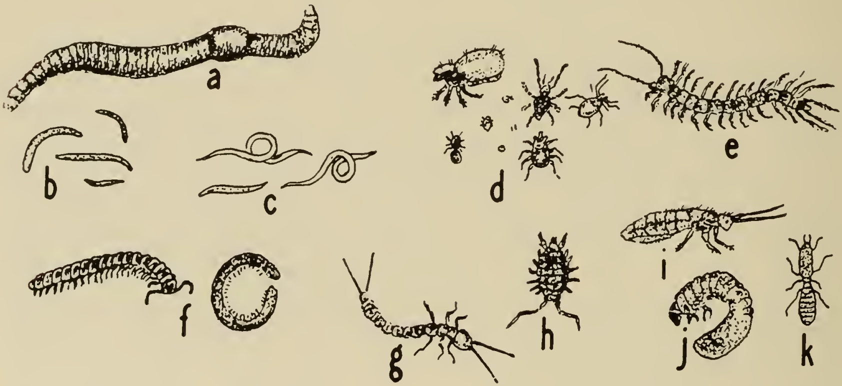


FIG. 3–9. Forest soil fauna: (*a*) Lumbricus earthworm; (*b*) Enchytraeids or white worms; (*c*) nematodes; (*d*) mites, ticks, and spiders; (*e*) centipede; (*f*) millipedes; (*g*) bristle-tail; (*h*) sow bug; (*i*) spring-tail; (*j*) white grub; (*k*) termite.

BIRDS

A forest supports at least two and often more birds per acre. The birds contribute to soil fertilization and periodically rework patches of forest litter in search of food or grit. The latter habit is particularly common to the partridge and related gallinaceous birds. Some of the birds, especially woodcock, provide soils with a network of small drainage wells which facilitate the infiltration of water.

A congregation of a large number of birds on an area may be as harmful as a congregation of animals. The overfertilization of the soil in the rookeries of the blue heron kills every plant of the ground cover and leads to a gradual deterioration of hemlock, yellow birch, and other trees. Even an unreasonably high population of domestic chickens is known to be detrimental to farm woodlots.

MAMMALS

There are several reasons for agreeing with the opinion of Jacks (1954) that fauna influencing the composition of soils "can consist of all sizes, from elephants to protozoa." Bear, deer, coyote, fox, raccoon, skunk, badger, and other undomesticated large fur-bearers—all trample forest grounds, dig the soil, and fertilize it with their manure. In certain regions scarification of the soil by wild animals has an indisputably beneficial effect on the establishment of natural forest reproduction, especially that of coniferous species. Vigorous growth of young seedlings is often correlated with deposits of the briquetted animal fertilizer. To a certain degree, the life activity of all forest-inhabiting quadrupeds exerts favorable influence on the properties of the surface humus layers of the soil and perhaps indirectly on the composition of the entire soil profile. It is not excluded that the development of the inert raw humus under many forest plantations of central Europe owes its origin to the annihilation of the important zoological components of the forest biome.

The influence of quadrupeds on soil properties acquires an entirely different aspect when the action of man concentrates their population to an unreasonable degree. The cow is an unusually well-behaved animal which would probably be beneficial to the forest and soils if its population were kept to a dozen head per square mile. A herd ten times as large ruins both forests and soils. The most detrimental effect of heavy grazing is the compaction of the surface soil by trampling livestock, an alteration which impedes the infiltration of water and subsequently leads to the loss of water, either through evaporation or runoff (Steinbrenner, 1951).

The soil-forming effects of mammals are considerably amplified as they diminish in size. Such effects attain their maximum with moles, shrews, and rodents, whose total weight often exceeds one ton per acre (Fig. 3–10).

European students of forest soils (Müller, 1887; Ramann, 1911; Bornebusch, 1930) gave the palm for soil cultivating activity to the mole. The tunnels and hills made by this efficient forest miner at times impart a conspicuous microrelief to forest grounds. The presence of the mole is supposed to serve as a reliable indicator of fertile "mull" soils with incorporated humus and abundant edaphon. In fact, in the opinion of some foresters, the names **mull** and **mole** are of the same origin. The mole's diet consists predominantly of earthworms, whose decapitated bodies are immured for the winter days in the walls of the channel, sometimes in numbers exceeding 1000 corpses in a single molerun.

In spite of all the indirect evidence of the mole's beneficial activities, its reputation as a soil-improving agent appears to be grossly exaggerated. The distribution of this animal is confined to soils which are not in need of cultivation, the task being performed by the earthworms. The excursions of the mole to the forest-adjoining fields are definitely detrimental to farming.

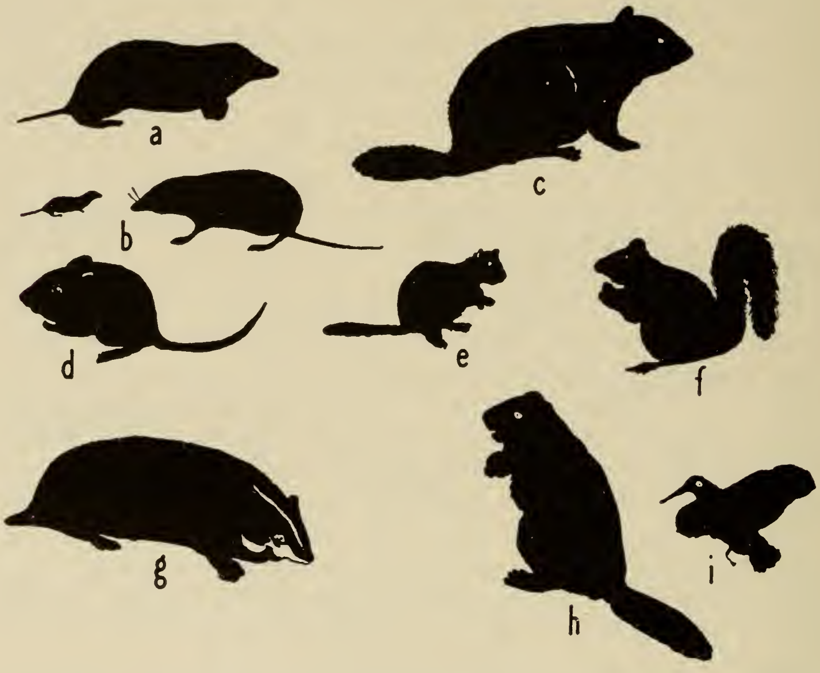


Fig. 3–10. Silhouettes of some forest soil-inhabiting or soil-cultivating vertebrates: (*a*) mole; (*b*) shrews; (*c*) woodchuck; (*d*) mouse; (*e*) ground squirrel; (*f*) gray squirrel; (*g*) badger; (*h*) beaver; (*i*) woodcock.

In forests of North America the shrews, close relatives of the moles, have a much greater silvicultural importance. These miniature, sharp-nosed creatures surpass the mole in numbers, speed of action, and especially appetite, their daily food consumption being several times the weight of their bodies. What is most important, shrews concentrate their activity in the litter and duff, the superficial organic layers of forest soils which are in need of reworking.

The passageways of the mole and shrew are often supplemented by the less regularly distributed burrows of the mouse, chipmunk, gopher, ground squirrel, woodchuck, mountain beaver, and other rodents. All of these animals contribute to the processes of humification and soil dynamics. Their distribution is determined not only by the supply of food but also by the physical conditions of the soil. For example, woodchucks attain greatest density on gravelly, sandy loams of glacial deposits. The chipmunk is one of the few inhabitants of strongly podzolized soils and sometimes has its storehouse of winter food in the indurated accumulative layers. Snowshoe rabbits establish their homesteads near alluvium and on swamp-border soils. Unlike the mole, shrews are common in podzolic soils. Prairie-forest soils are inhabited by gophers, prairie dogs, and blind mole rats. The profiles of these soils are often marked by abandoned, soil-filled passages and nests of rodents, the so-called "krotovinas." By recording the distribution of krotovinas, Dokuchaev was able to trace the boundaries of the relic prairies.

In many instances, the benefits of rodents as soil cultivators are outweighed by their disorderly conduct in the forest, especially their destruction of seedlings and young trees. Therefore, in forest areas, predisposed to multiplication of rodents, attention should be given to the preservation of the weasel and other predatory animals. In Dokuchaev's opinion, certain rodents "are capable of converting any fertile blackearth prairie into a genuine desert."

One member of the rodent's clan, the beaver, causes an unparalleled alteration of soil conditions. The deterioration of the dams abandoned by beavers leaves behind large flowage areas of deoxidized and hydrolyzed soils, saturated with ferrous iron, hydrogen sulfide, and other "swamp gases." The fixation or depletion of available nutrients and the destruction of beneficial symbiotic fungi are among other adverse effects of the impounded water. These deficiencies exclude soils of abandoned beaver flowages from the class of productive lands for a period of several decades (Wilde, Youngberg, and Hovind, 1950).

The mystery which for Man in Nature lies
We dare to test, by knowledge led;
And that which she was wont to organize,
We crystallize instead. —Goethe, *Faust*

4

Forest humus

Natural humus forms and their designations. The path from fallen leaves to the salts of the earth leads through the realm of invisible creatures which are engaged in the process of "humification" or "mineralization" of organic remains. This transformation has occupied students of nature for many centuries. Aristotle understood that organic remains undergo in soil a "process of digestion" and visualized soil as the "stomach of plants" (Laatsch, 1954). One of the intermediate products of organic matter decomposition, the dark amorphous residue, or "humus," was the mysterious substance that aroused the curiosity of alchemists. During the past hundred-odd years, humus has become the subject of scientific investigations, initiated by Berzelius (1839) and Mulder (1840). However, the equipment of the modern laboratory proved to be only slightly more efficient than the bellows of the medieval cellar in revealing the chemical structure and behavior of the substance which is "the product and the source of life." The texts on soils show in their discussions of humus the greatest disproportion between trustworthy information and speculative assumptions. The largest share of concrete knowledge in this narrow sector of soil science was accumulated by students of forest soils, not by scientists of agronomical orientation. According to Baker (1950), a check of a recent bibliography on forest soils showed that nearly 80 per cent of the papers dealt with problems of humus. This should be explained by the fact that the humus is the principal agent in the development of forest soils and the all-important natural fertilizer of trees.

Hundeshagen (1830) was the first forester to recognize the silvicultural and soil-forming importance of the processes of organic matter decomposition and the development of different humus forms. Unfortunately, his observations passed unnoticed, and only four and a half decades later Emeis (1875) suggested classification of forest humus into three types: one made up of well-decomposed organic matter incorporated with the mineral soil and containing nitrogen in the form of "nitric acid," and the other two made up of "raw" organic remains.

Shortly after the appearance of Emeis' paper, Müller (1879, 1884) issued two monographs on the natural humus forms, their relation to forest growth, and their effects on soil development. He termed the superficial deposit of organic remains **mor** humus and the intricate mixture of amorphous humus and mineral soil **mull** humus. Müller's reports attracted wide attention, far beyond the boundaries of his native Denmark. The simultaneous publication of Darwin's work on earthworms and vegetable mold (1881) still further increased general interest in humus. For some time it appeared that Müller's two principal types, mull and mor, placed the problem of humus classification on a sound scientific basis.

However, later proposals made by Ramann (1893, 1905, 1911) and by other authors introduced a number of misconceptions and brought about nomenclatural chaos (Waksman, 1938). The simple concept of superficial organic matter was at one time or another referred to as "mor," "mår," "moor," "torf," "dry peat," "raw humus," "surface humus," "duff," and "holorganic layer" (Fig. 4–1). In time,

FIG. 4–1. A nearly 5-inch-thick deposit of matted organic remains, the so-called mor layer; a feature unique to forest soils that manifests the retarded decomposition of forest litter and at times the arrested return of available nutrients.

classification of forest humus grew into an ideological and terminological monstrosity.

The existing turmoil did not arise from the disagreement of opinionated authors of different classifications, but was a consequence of generally insufficient knowledge of the subject, intrusion of unqualified generalizations, and underestimation of the pedological and silvicultural importance of humus layers. To a great degree, the development of a workable system of forest humus classification was handicapped by the fact that the recording of the visible morphological features was rarely supplemented by the study of the concealed biological, physico-chemical, and nutritional characteristics of humus.

In this book an attempt is made to present the available information in a simplified form and to correlate the important characteristics of humus layers with various aspects of silvicultural practice. Foremost emphasis is placed on the genetic features of different humus forms in the belief that such features are in the key position for investigation of all other properties of humus layers. As far as possible, the approach of the authors of recently introduced classifications has been synchronized with the principles established by Müller and his followers.

Origin and morphology of humus layers. The process of humification of organic remains is often initiated before the humus-forming material has reached the ground. Each time we delight ourselves in the taste of a fragrant raspberry we consume as a premium over a hundred microscopic mites who derived their livelihood from the same source; each leaf detached from its twig carries to the soil a considerable number of organisms engaged in destruction of tissues. And so it is with all animals crawling and creeping on the forest floor; the instant of their death signifies an explosion of new life—feast and multiplication of the humification agents. Hence, the surface layer of a forested soil presents a dynamic entity in which the energy of dead remains is transferred to new organisms and new compounds.

Depending on the type of organisms employed in the breakdown of organic remains, the surface layer of woodlands acquires a highly diversified morphology. It may appear as a mere "litter," a scattering of leaves and needles, or as a thick mor layer of compressed organic remains in all states of division. Either of these extreme forms of surface debris may overlie a dark humus-enriched horizon or a light-gray mineral soil that exhibits no trace of "black matter." In some cases such a gray soil is a leached or "podzolic" horizon impoverished in humus and nutrients; in other cases it is a "leucorganic" layer enriched in nitrogen and other nutrients by infiltration of colorless humates.

Thus, organic layers include three principal fractions: partially decomposed organic remains resting on the surface of mineral soil, which may be named **ectorganic fraction** or **ecto-humus;** dark-colored, finely dispersed organic matter incorporated with the mineral soil by the action of organisms, by infiltration, or as a residue of root systems, that is, the **endorganic fraction** or **endo-humus;** pale-colored organic suspensions or pseudo-solutions not detectable by ocular examination, which may be designated as the **cryptorganic fraction** or **crypto-humus.** The composition and the relative proportion of these fractions are correlative with environmental conditions and give rise to different humus forms.

It is customary to subdivide the ectorganic humus layers into several subhorizons: **forest litter, fermentation** or ***F*** **layer,** and **humified** or ***H*** **layer.** Such a detailed subdivision, however, is often precluded by the diffused boundaries of the subhorizons and is not always justified for practical purposes.

The influence of climate and substratum determines to a considerable degree the output of organic remains and the rate of their decomposition. This, in turn, delineates two distinct forms of humus layers: **megorganic layers** and **oligorganic layers.**

Megorganic layers develop in environments which produce large quantities of plant material or retard decomposition of organic remains; such layers are characterized by a high or at least appreciable content of organic matter, free or incorporated. They include **rich mull** and **heavy mor** layers. The occurrence of these layers is largely confined to forest soils found in cold and temperate regions. **Oligorganic** layers are prevalent under conditions where organic remains undergo extremely rapid decomposition or where forest stands produce sparse amounts of litter. Such layers include several distinct types: **velum,** a mere scattering of foliage; **crypto-mulls,** pale-colored horizons enriched in nitrogen; **lean swards,** endorganic sod layers originated from the roots of xerophytic grasses; **hydrosolic melazones** or dark stains carrying a negligible content of nitrogen; and **lean mors** or **felts,** compacted ectorganic layers less than one inch thick.

The principal organisms which contribute to the formation of humus layers by their life activity as well as by their dead tissues include earthworms, nematodes, crustaceans, mites, millipeds, other members of the arthropod phylum, protozoa, fungi, bacteria, actinomycetes, trees, shrubs, heath plants, grasses, mosses, lichens, and other ground cover vegetation.

Depending upon the predominant agent of humus development, organic layers may be subdivided into the following genetical groups: **foliogenous**, formed by superficial parts of plants; **rhizogenous**, made up chiefly of remains of root systems, especially those of grasses and heath plants; **zoogenous**, formed by earthworms and arthropods; **microbiotic**, developed in the absence of macroanimal forms by a diversified population of bacteria, fungi, actinomycetes, protozoa, and nematodes; **mycelial**, consisting in a large part of decay-resistant tissues of fungi. Under conditions of impeded drainage, aerobic organisms are replaced, at least in part, by anaerobic organisms, and the organic remains are subjected to strong hydrolysis in the presence of reduced compounds. The resulting process of "putrefaction" or anaerobic fermentation of the methane or hydrogen type gives rise to **saprogenous** humus layers.

Figure 4–2 illustrates several of the representative forest humus forms. The more important types of humus layers, developing under the influences of different environmental conditions and biotic factors, are described in the following synopsis. Although space limitations permit only brief descriptions, the importance of the subject matter must not be underestimated. The humus layer serves as a major factor of soil development and hence the knowledge of humus forms constitutes an essential prerequisite for the classification of soils on a genetical basis. In current practice, foresters have only infrequent opportunities to dig trenches and analyze the entire soil profile. However, they can always spare a few moments for the examination of the topmost portion of the soil—which often mirrors the concealed soil properties and which determines the outcome of many silvicultural endeavors.

MAJOR TYPES OF FOREST HUMUS LAYERS

Velum. The term "velum" is derived from the Latin word meaning veil (Wissotzky, 1930). It is applied to the embryonic humus layers consisting largely of the previous year's loose or friable litter which rests on a pale-colored eluvial horizon **impoverished in nitrogen.** The content of the total nitrogen in the surface mineral soil is usually below 0.05 per cent.

This typical representative of oligorganic humus layers is a result of the energetic activity of the soil population and an intensive leaching of the products of organic matter decomposition.

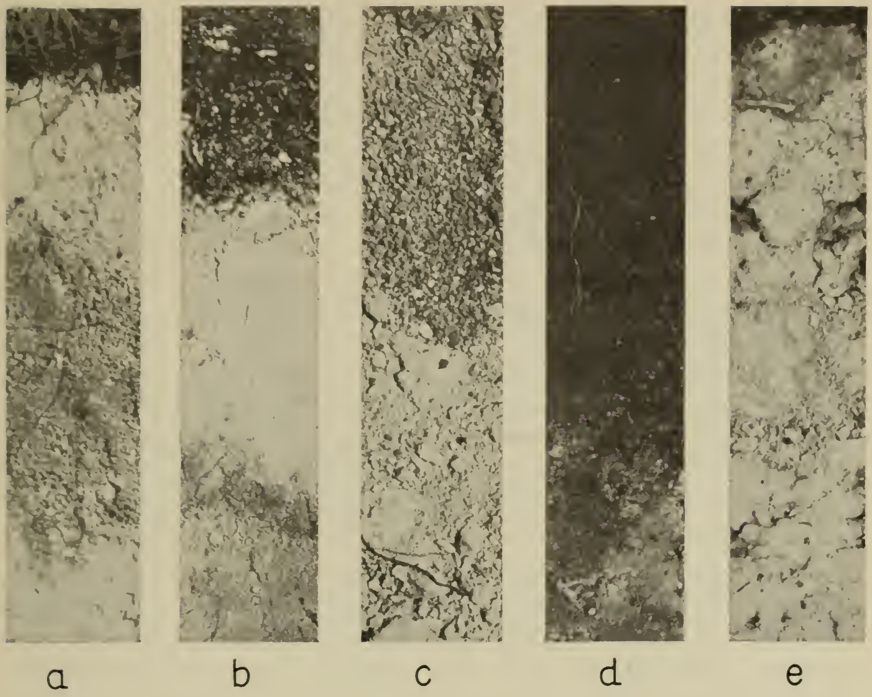


FIG. 4–2. Representative forms of forest humus layers: (*a*) matted mor, partly lignified mycelial ecto-humus of a strongly podzolized lacustrine clay; (*b*) sog mor, peatlike saprogenous ecto-humus formed on a gley podzol; (*c*) earthworm crumb mul, zoogenous endo-humus of a weakly podzolized silt loam influenced by a deep ground water table; (*d*) prairie sward, rhizogenous endo-humus of a forest-invaded sandy loam soil; (*e*) crypto-mull, leucorganic endo-humus of a yellow podzolic silt loam.

Crypto-mull. This leucorganic endo-humus is similar to velum except that litter rests on pale-colored soil **enriched in nitrogen** by infiltration of humates. The depth of the humate infiltration, varying from about one to three feet, may be best established by the Kjeldahl analysis. As a rule, the upper portion of the mineral soil contains more than 0.1 per cent of the total nitrogen (Wilde, 1951).

Crypto-mull is distributed in warm and moist climates, predominantly on fine-textured soils. It owes its existence to warm and humid conditions under which the nearly instantaneous and complete breakdown of litter is accompanied by the destruction of dark pigmentation. In some instances soils with crypto-mull humus support heavy stands of exacting tree species.

Microbiotic mull. The plant remains in this endorganic type undergo gradual decay, rather than the disintegration or destruction caused by arthropods or earthworms in zoogenous types. The litter, therefore, is characterized by the presence of coarse fragments of leaves which tend to resist decomposition. It preserves a reasonably loose structure, although it has a tendency to form localized "lumps." The dark humus horizon, or mull layer proper, has a finely aggregated, massive, or single-grain structure; it varies in thickness from a few inches to nearly two feet. The carbonized colloidal residue is distributed in the soil profile largely in the form of suspensions or pseudo-solutions (Mařan, 1944). In some instances, the translocation of organic matter is aided by migration of microorganisms, particularly nematodes.

The development of microbiotic mull was at times attributed to purely chemical processes and this form identified with "pseudomull," "abiotic orthumus" (Lang, 1932), or "chemorganic humus" (Frei, 1946). Investigations of the microbiological characteristics of forest soils, however, failed to verify the existence of the "abiotic" humus layers.

Mull layers formed predominantly by the action of microorganisms are widely distributed throughout the forests of the world and have numerous morphological varieties determined by the texture of the mineral soil, content of organic matter, and thickness of the endorganic layer. Such varieties may be characterized by a combination of the following terms: lean, rich, shallow, deep, sandy, fine-textured, aggregated, and massive. The macroscopic appearance of the last variety, however, may be misleading because microbiotic mulls often develop grain structure of stable microscopic aggregates.

Earthworm mull. This is the prototype of the mull group and the best-known representative of the zoogenous or coprogenous humus. It received the particular attention of both Müller and Darwin. Because of the leading part which earthworms play in the development of this humus form, Darwin suggested that the expression "animal mould" might be more appropriate than "vegetable mould."

The devouring of organic debris by worms and the burrowing habits of these animals usually leave a thin sporadic layer of litter and convert the surface soil into an intimate mixture of mineral and organic matter. The structure of the endorganic horizon is determined by the size of earthworms: *Lumbricus* and other large worms produce coarse or crumblike aggregates of castings; small worms produce fine, grainlike aggregates.

Earthworm mull layers form surface horizons of many soils in the temperate zone. As a general rule the occurrence of this humus type is confined to fine-textured soils influenced by the ground water or seepage. The cover of deciduous species is predominant, but occasionally earthworm mulls are found under mixed hardwood-coniferous and even pure coniferous stands. The rate of forest growth on soils with this type of humus varies from many thousand board feet to a few cords per acre. Hence the often-expressed view that the earthworm mull symbolizes soils of high productive capacity is not warranted by facts.

Arthropod mull. The activity of crustaceans, mites, millipeds, and insects causes the disintegration or pulverization of forest litter and leads to an accumulation of organic remains in the form of a detritus enriched in castings and shells of animals. Depending upon humus-forming organisms and the nature of the litter, the organic layer attains an appearance of brownish bran, ground dark-brown coffee, or very fine black sawdust (Hartmann, 1951). In a pure form, arthropod mull is essentially a superficial deposit and, from a strictly morphological viewpoint, should be regarded as a transition to the mor group of humus. In some instances the depth of the ectorganic layer of arthropod mull exceeds six inches, and the loss on ignition approaches 70 per cent. If it were not for the ambiguous homonym, this form should have been designated as "mor-like mull" or "mull-like mor."

The distribution of arthropod mull embraces a wide range of climatic conditions, including those of the cold and humid belt of Canada. In the majority of cases this type is confined to soils derived from calcareous rocks and deposits. The yields of forest stands on soils with this humus type vary from a few cords, produced by struggling oaks on skeletal limestone soils in the American Midwest, to 30 Mbf per acre, produced by spruce and other conifers on calcareous clays of Canada.

Sward. The term "sward," synonymous with "turf" and "sod," is defined by Webster as "the upper stratum of earth and vegetable mold filled with the roots of grass and other small plants." This definition fits admirably the concept of a rhizogenous endo-humus developed by incomplete decomposition of roots of herbaceous vegetation and found universally in prairie, semidesert, and alpine meadow regions. When either of these formations is invaded by the forest, the humus layer may remain rhizogenous in nature for a period of several centuries (Pierce, 1951); only gradually does it undergo a metamorphosis into zoogenous mull or other forms of forest floor. When the small density of forest cover allows the existence of a solid grass cover, the rhizogenous humus layers of prairie-forest and desert-forest ecotones are maintained for an indefinite period by root systems of herbaceous vegetation. An apparent morphological similarity between sward and earthworm mull layers is purely coincidental; as often as not, sward layers harbor no earthworms.

Depending upon climatic conditions and the nature of herbaceous cover, several types of rhizogenous endo-humus may be recognized, such as: **prairie sward, alpine sward**, and **grassland** or **semidesert sward.** In a more detailed way, these types may be classified as: **bluejoint sward, gramma sward, fescue sward,** and **bunchgrass sward.** Swards of different geographic regions vary in thickness from two feet (prairie sward) to a few inches (grassland sward); their content of organic matter ranges from a fraction of 1 per cent to more than 20 per cent (alpine sward).

Duff mull (Amphimorph). This is a stable type of ectendo-humus, forming the transition between mull and mor. It is made up of forest litter, partly disintegrated organic debris or "duff," and a layer with incorporated humus. It is common on a vast area of forested plains and mountains. This type is the result of the activity of several groups of organisms including microbes, worms, and arthropods. It has several pronounced morphological varieties, determined by the nature of its ectorganic and endorganic fractions, for example, **friable duff-crumb mull, arthropod duff-grain mull,** and **matted duff-sand mull.**

Fen mull. This type of saprogenous endo-humus of mildly acid or alkaline reaction is found on lowland soils underlain at a shallow depth by ground water enriched in bases. It is composed of sparse forest litter and a mucklike layer of partly mineral, partly organic material varying in depth from about two to eight inches. The organic matter is finely dispersed and usually saturated with calcium and magnesium. The name for this hydromorphic form of humus is construed on the basis of terminology for organic deposits advanced by Dr. Oswald of Sweden (Tacke, 1929).

Fen mull is formed under the influence of hydrolysis and activity of anaerobic bacteria, protozoa, and other inhabitants of waterlogged soils. Periodic saturation of the humus layer does not necessarily prevent the existence of a rich population of organisms, including enchytraeids and larger worms. It is possible that some free oxygen is provided by algae.

Fen mull is distributed throughout the entire broad zone of mesophytic hardwoods, being particularly common in the prairie-forest region. Soils with this type of humus support forest stands of moisture-loving deciduous trees that have a very slow rate of growth and high percentage of cull.

Lean mor (Felt). This diminutive variety of foliogenous ecto-humus may be regarded as "consolidated velum" or as "embryonic mor." It consists of a thin layer of partly decomposed, laminated or compressed litter, interwoven by fungus mycelia or roots of ground-cover vegetation. It does not exceed ¾ inch in thickness and is underlain by a humus-free mineral soil (Hoover, 1949).

Felt layers are encountered most frequently on soils of the subtropics where they appear to form a stable type of forest humus development. Similar oligorganic layers are also found in mountain forests of conifers or hardwoods with rhododendron ground cover (Ohmasa, 1951). In many instances, felt layers represent a temporary successional phase in soil development, caused either by natural alterations of forest milieu, by fire, or by planting of coniferous species outside their native regions.

Crust mor. The thin, firmly consolidated, crustlike layer of ecto-humus is derived largely from tissue of *Cladonia* lichens. It occurs predominantly on rock outcrops, aeolian sands, and burnt-over areas. Soils with this type of forest floor usually support slow-growing conifers, especially pines and black spruce. The shallow depth of the humus layer is largely due to the poverty of soil and sparse production of organic matter by stands lacking understory; the activity of ascomycetous symbionts of the lichen, especially their strong acidifying effect, may be a contributing factor. Lichen mor retains uniform morphology through the enormous area of cold and temperate zones.

Root mor. A tenacious ectorganic layer of this type is interwoven by a dense network of roots of ground cover plants. It is found mainly on strongly leached sandy or sandy loam soils supporting conifers with ground cover of Vacciniaceae, particularly blueberries. This form of rhizogenous ecto-humus was previously described in detail by Romell and Heiberg (1931) under the name of "fibrous mor." Morphological varieties are determined largely by the nature of the roots of humus-forming plants. Occasionally a variety of rhizogenous mor is formed by the fine roots of hardwoods, especially hard maple and beech, growing on acid soils.

Ligno-mycelial mor. This typical representative of "raw humus" consists of a firmly consolidated ectorganic layer derived in part from fungus mycelia penetrating the partly decomposed forest litter. It is sharply delineated from the bleached mineral soil and varies in thickness from two to about eight inches. This type is largely confined to soils which support coniferous and hardwood-coniferous stands with ground cover of acidophilous, so-called "raw humus" plants.

Under unfavorable conditions, particularly on soils depleted in nutrients, the retarded activity of saprophytic organisms may convert the ectorganic layer into a pathological form of inert lignified mor (Duchaufour, 1953). This alteration greatly reduces the release of available nitrogen and other nutrients which become fixed in the decay-resistant fungus mycelia. In time, the interruption of the fertility cycle leads to the malnutrition and gradual deterioration of forest stands. The concentration of feeding roots in the shallow superficial layer is another negative effect of this humus type. The breakdown of the natural self-fertilizing mechanism of forest cover is especially common in environments adversely modified by man's activity and in severe boreal climate (Wittich, 1952; Siren, 1955). Outside of such conditions, the occurrence of thick mycelial or lignified mor layers is not necessarily correlated with the depressed rate of forest growth; soils with this type of forest floor are known to support stands of white pine and spruce whose yields approach 50 Mbf per acre.

Sog mor. This hydromorphic or saprogenous form consists of a thick layer of ecto-humus of macerated or fibrous structure. It is underlain either by an ash-gray leached horizon or a layer stained with humates. This type of humus is confined to the boreal forest regions where it occurs on soils with a ground water table at a shallow depth.

The development of sog mor proceeds, in part, under hydrolysis and periodic anaerobic fermentation or saprogenation. These processes, however, are often supplemented by the activity of various other humus-forming agents, including fungi and arthropods. The entire course of biological activity of these layers is greatly affected by periodic fluctuations of the ground water table. The forest cover is composed predominantly of "swamp-border" coniferous and deciduous trees.

Occasionally, saprogenous mor is formed on water-retaining rock outcrops, particularly those of calcareous origin; the latter variety was classified as "alkaline raw humus" or "rendzina mor" (Galloway, 1940).

Moss mor. This type of forest floor is transitional between mor humus and peat. It is characterized by a peculiar "stratum superficiale," or S-layer (Forsslund, 1943), consisting of live *Sphagnum* and other mosses. Under the climatic conditions of boreal regions and high mountains, excessive humidity permits growth of bog moss species on upland soils as well as in depressions. Once established, bog mor produces radical changes in the ecological status of the area by decreasing the aeration and temperature of the soil. Aside from unfavorable physical effects, this type causes impoverishment of the root-inhabited zone through permanent fixation of available nutrients by the tissue of moss cover. In time the combination of all these adverse influences leads to the replacement of the forest by *Chamaedaphne* muskeg, *Sphagnum fuscum* bog, and similar types of xerophytic swamps that deny sustenance to trees.

Figure 4–3 illustrates schematically the morphology of the important types of humus layers. Figure 4–4 outlines the general

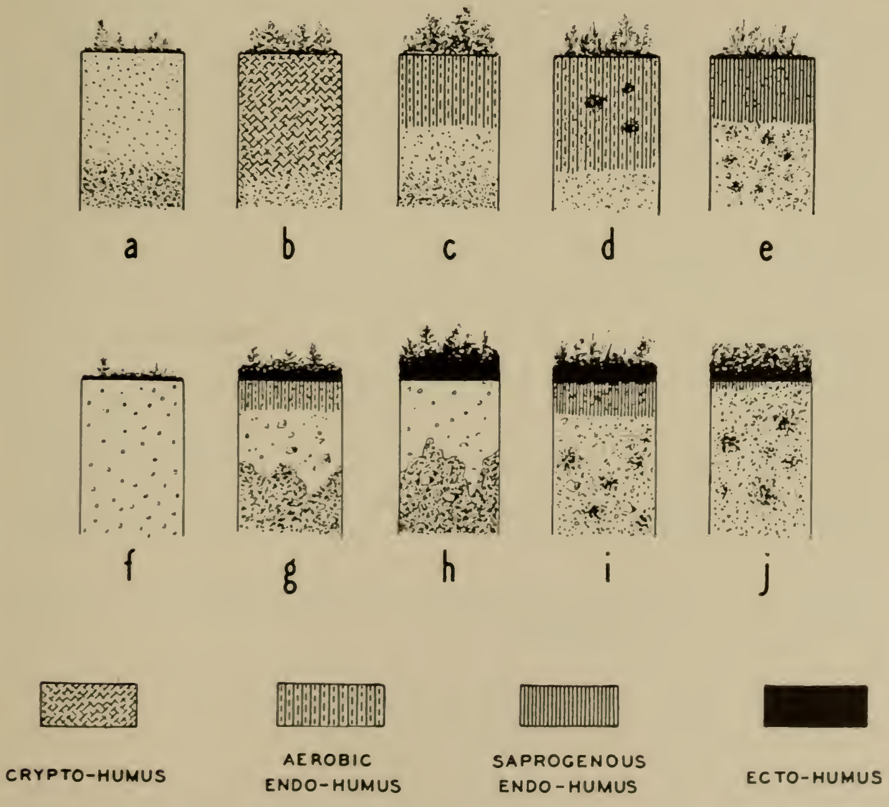


FIG. 4–3. Profiles of the major types of forest humus layers (schematic presentation): (*a*) velum, oligorganic ecto-humus; (*b*) crypto-mull, leucorganic endo-humus; (*c*) earthworm mull, zoogenous endo-humus; (*d*) prairie sward, rhizogenous endo-humus; (*e*) fen mull, saprogenous endo-humus; (*f*) lichen crust mor, oligorganic ecto-humus; (*g*) duff mull, amphimorphic ectendo-humus; (*h*) mycelial mor, mycogenous ecto-humus; (*i*) sog mor, saprogenous ectendo-humus; (*j*) moss mor, microbiologically inert Sphagnum ecto-humus.

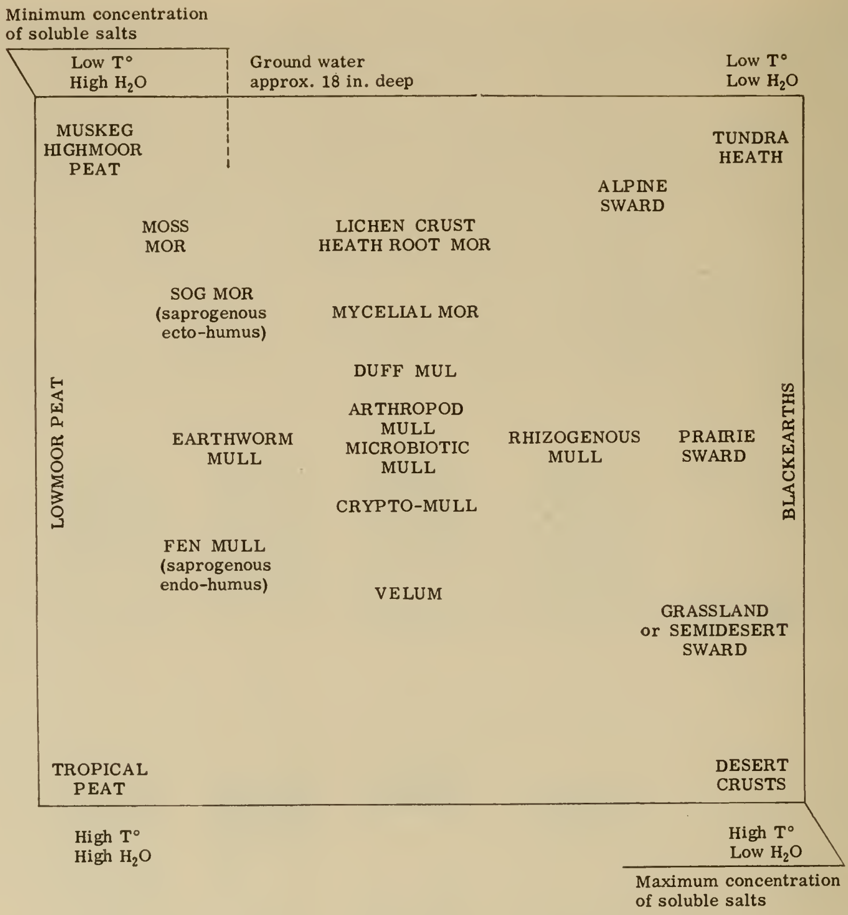


FIG. 4-4. General trend in the distribution of genetic types of forest humus in relation to temperature and moisture.

trend in the distribution of the major forms of forest humus in relation to climatic conditions.

CHEMICAL AND MICROBIOLOGICAL PROPERTIES OF FOREST HUMUS

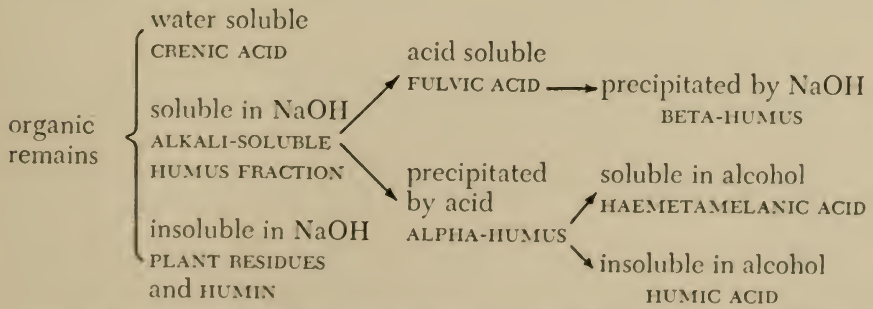
Most of the existing classifications of forest humus are based on the visible morphological features of the ectorganic and endorganic layers. This is apparently a legitimate approach, but it is not one that can be accepted without restrictions and amendments.

The ocular determination of the morphology of forest humus is not a simple matter and invariably leaves the specialist or practitioner wavering between objectivity and subjectivity. Moreover, a classification based solely on external characteristics may easily lead to hair-splitting details and a multitude of abstract concepts divorced from their context. For this reason, morphological classification of humus should, as far as possible, be supplemented by the determination of concealed chemical and microbiological properties. However, because of the complexity of humus, chemical or microbiological analyses usually provide clues rather than concrete answers.

Because of their potent action, acids and alkalies for centuries have served as important tools of chemical research. Alternate addition of these reagents always brought something into solution and then produced a precipitate. This was thought to be the way to obtain gold, homonculus, elixir of life, or humus—the "spirit of the soil."

By treating organic remains with hydrochloric acid and solutions of ammonia and sodium carbonate, Sprengel (1826) isolated an amorphous black substance which he called "humic acid." This mixture of various compounds of unknown structure is negatively charged, has a high base exchange capacity, and produces soluble salts with alkalies and insoluble salts with alkaline earths and heavy metals. It takes part in the development of stable clay-humus complexes and iron humates, and liberates carbon dioxide and silicic acid from easily weathered soil minerals.

The isolation of "humic acid" led to the separation of many other chemically indefinite fractions, obtained by treatment of organic matter with acids, alkalies, and alcohol. Depending on the mode of extraction, these colloidal sols were given different names, such as crenic acid, fulvic acid, ulminic acid, humin, alpha-humus, beta-humus, and haemetamelanic acid. A general scheme for separation of these fractions follows.



The terms in the above outline do not refer to exact chemical compounds but represent fractions obtained by conventional methods of extraction.

More recently, claims were advanced that a treatment with mineral acids followed by acetyl bromide dissolves the readily decomposable fraction of organic remains (Springer, 1938). The insoluble residue is called "stable humus" (Dauerhumus). The fraction soluble in 80 per cent sulfuric acid and consisting largely of carbohydrates and proteins is considered to be "nutrient humus" (Nahrhumus). Dead organic remains as yet unconverted to either of these groups are referred to as "reserve humus."

Even though students of humus from Sprengel to Springer fractionated organic remains for a period of more than one hundred years, there is yet only fragmentary evidence as to the importance of different extractibles in the processes of soil development and the life of plants. Obviously, the acquisition of reliable information by these techniques was greatly handicapped by the fact that extractibles from different organic remains vary in their composition. Moreover, the chemical structure of different fractions remained inexplicable because of the generally limited knowledge of complex organic compounds. Only recently the use of chromatography and other modern techniques permitted evaluation of different fractions in terms of more definite chemical entities, such as uronides, phenolic glycosides, different sugars, amino acids, and lignin-like compounds (Fraser, 1955).

A modified approach toward humus analysis was suggested by Waksman (1938). He used ether, cold and hot water, alcohol, and strong acids for extraction of polymerized substances that approached in their composition carbohydrates, lignin, protein, and other compounds of fairly well known structure. The relative contents of these fractions bring out not only the differences between the forms of humus but also the differences between the humified material and the original residue from which it was derived. Table 4–1 illustrates the composition of several types of humus layers as revealed by proximate analysis.

Under certain conditions, the extractibles determined by proximate analysis may be further separated into more definite chemical compounds. Among such procedures, the determination of the polyuronide content of the soil on the basis of the amount of CO_2 evolved on heating with 12 per cent HCl has received particular attention.

Besides the proportions of different organic constituents, certain physical and chemical properties characterize the origin and sometimes the ecological effects of humus. Among such properties those which should particularly be mentioned are reaction, total acidity or alkalinity, exchange capacity and degree of base saturation, specific conductance, bulk density, content of total and available nutrients, and carbon-nitrogen ratio.

Mull and mor humus are not synonymous with "sweet" and "sour" humus, as was believed originally. The reaction of humus layers varies within the very wide limits of pH 4.8 to pH 8.5 for mull humus and pH 3.0 to pH 8.0 for mor humus. However, within each of these morphological groups the pH value determines the composition of the microbiological population and the nature of metabolic by-products. The ecological effects of the pH value are often modified by the buffering capacity of organic matter and the resulting total acidity or total alkalinity. Specific conductance of the humus suspension is closely correlated with the content of soluble salts and is indicative of the general level of soil fertility. Specific conductance at a certain pH level, or the pL value (Nicol, 1954), serves as another characteristic of humus layers.

TABLE 4–1

Proximate Chemical Composition of Different Types of Forest Humus

(H. M. Galloway and W. E. Patzer)

Constituents	Acid mycelial mor	Alkaline rendzina mor	Arthropod bran mor	Lumbricus crumb mull
	Per cent of dry material on ash-free basis *			
Ether soluble fraction	3.42	0.26	2.94	0.46
Hot water soluble fraction	5.22	2.42	3.78	1.83
Alcohol soluble fraction	4.65	2.12	2.00	3.17
Hemicelluloses	6.84	7.82	3.35	2.94
Cellulose	6.08	2.21	4.07	1.60
Lignin	41.51	32.72	39.71	31.16
Crude protein	11.11	12.41	11.60	19.02

* Ash contents: acid mycelial mor, 4.55 per cent; alkaline rendzina mor, 14.46 per cent; arthropod bran mor, 12.85 per cent; Lumbricus crumb mull, 90.12 per cent.

Base exchange capacity is closely related to the content of lignin-like substances and may serve as an indicator of the degree of humus decomposition. The base exchange capacity of raw humus ranges from 40 to 100 m.e. (milliequivalents) per 100 g. The base exchange capacity of mull humus is seldom greater than 30 m.e. per 100 g. because of the high content of mineral matter; however, the exchange capacity of the organic fraction itself may exceed 200 m.e. per 100 g.

The nutrient content of humus is a function of three variables: type of humus, nature of underlying mineral soil, and composition of forest stand. Mull types have considerably lower concentration of nutrients than raw humus types. Fine-textured soils derived from parent materials rich in nutrient-bearing minerals produce humus with a high content of nutrients, whereas sandy or siliceous soils produce humus poor in nutrients. Light-demanding species, particularly pines, tend to accumulate less nutrients in their litter than do shade-tolerant trees, such as spruce, maple, and basswood (Alway, Kittredge and Methley, 1933). One of the important criteria for judging the degree of humification is the carbon-nitrogen ratio which ranges from about 11 in mull types to above 50 in mor types (Mader, 1953).

Although humus influences the development of plants through its physico-chemical, biological, and catalytic effects, a close correlation has been shown between the nutrient content of humus and the growth of forest seedlings under controlled conditions (Fig. 4–5). Table 4–2 illustrates the physico-chemical composition of several representative humus layers.

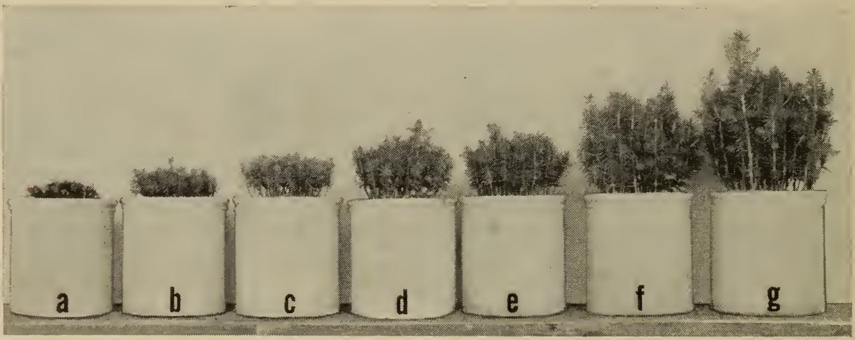


Fig. 4–5. The growth of two-year-old Norway spruce seedlings raised in quartz sand with addition of 4 per cent by weight of different types of organic remains: (*a*) check; (*b*) moss peat; (*c*) sedge peat; (*d*) hardwood crumb mull; (*e*) red pine duff; (*f*) hemlock duff; (*g*) hardwood-hemlock duff. (After Wilde, Buran, and Galloway, 1937.)

Aside from mineral nutrients, humus contains specific organic compounds which are beneficial to the growth of higher plants. These "growth-promoting" or "growth-regulating" substances, known as "phyto-hormones" or "auxins," are produced by microorganisms in the course of decomposition of plant remains. The stimulation of root growth in cuttings of conifers and other trees by beta-indole acetic acid and other auxins is a striking example of hormone action. The growth substances are present in soils in minute concentrations; an artificially increased concentration of these substances effects an abnormally rapid growth of plants terminated by death (Went, 1935; Bonner, 1937; Schopfer, 1943).

TABLE 4-2

PHYSICO-CHEMICAL CHARACTERISTICS OF REPRESENTATIVE TYPES OF HUMUS LAYERS

Type of humus layer	Bulk density	C/N ratio	Exchange capacity	Total exchangeable bases	Spec. conductance millimhos	Redox potential m.v. at pH 7.0	Catalytic capacity mm. Hg.
			m.e. per 100 g.				
Crypto-mull (x), pH 6.7	0.97	12.3	27.7	24.5	0.12	−53	223
Microbiotic mull (A_1), pH 5.9	1.02	11.1	31.6	23.9	0.09	+17	347
Earthworm crumb mull (A_1), pH 5.3	0.79	15.0	32.4	17.8	0.13	−40	382
Arthropod fine mull (H), pH 6.7	0.32	21.0	102.5	89.4	0.32	+21	14
Fen mull (A_1), pH 7.5	0.57	18.1	47.3	49.0°	0.23	−72	127
Bran mor (F), pH 5.5	0.25	19.1	67.3	43.5	0.47	−68	57
Crust mor (F), pH 4.2	0.11	30.6	17.7	4.1	0.03	−241	14
Ligno-mycelial mor (F + H), pH 4.1	0.14	37.2	103.3	19.7	0.11	−192	27
Moss mor (S + F), pH 3.7	0.08	39.2	114.9	9.1	0.09	−132	11

° Presence of free carbonates.

Humus combines with iron to form some compounds in which iron is available to plants and microorganisms in soils of an acid or an alkaline reaction. This property of humus is of particular importance in relation to the nutrition of forest trees, old stands as well as nursery stock. The discoloration or "chlorosis" of seedlings is common on alkaline nursery soils depleted in organic matter. The beneficial effects of humus upon the availability of phosphorus and other nutrients have also been observed on numerous occasions (Prianischnikoff, 1923).

The origin of humus and the intensity of biological processes are sometimes determined by direct count of humus-inhabiting organisms, such as earthworms, nematodes, arthropods, fungi, and bacteria. Analyses of this kind are usually supplemented by microscopic examination of humus layers (Hartmann, 1951). The intensity of microbiological processes is also manifested in the liberation of carbon dioxide, the consumption of oxygen, the heat of fermentation, the release of soluble nitrogen, and the rate of cellulose and protein decomposition (Richard, 1945; Wilde and Voigt, 1955). A quantitative record of these processes may serve to indicate the nature of organic remains (Němec, 1928; Waksman, 1938; Davey and Wilde, 1955). It should be noted, however, that natural environment is an extremely important factor in the activity of organisms; hence, the results of biological investigations of humus under optimum laboratory conditions have but relative significance. Microbiological characteristics of several types of humus layers are given in Table 4–3.

Under the influence of hydrogen peroxide, organic remains liberate free oxygen. This catalytic capacity depends upon a number of conditions, such as activity of microorganisms, the presence of catalase, reduced compounds of iron and manganese, and the nature of colloidal substances. From a scientific viewpoint this effect of soil or humus has a questionable significance, but empirical observations suggest that the catalytic capacity is correlated with the level of energy material and the density of microbiological population. In many instances, catalytic capacity reflects with a rather remarkable accuracy the genetical type of forest humus. It is sufficient to mention that catalytic capacity of *Sphagnum* peat is zero; it is very low in true mor layers but high in mulls, and especially high in humus layers of prairie soils and chernozems.

TABLE 4–3

MICROBIOLOGICAL CHARACTERISTICS OF REPRESENTATIVE TYPES OF HUMUS LAYERS

	Cellulolytic activity	Proteolytic activity	Nitrification capacity NO_3 (ppm.)	Aerobic bacteria	Anaerobic bacteria	Fungi	Effect of volatile substances, root growth (mm.)
	Tensile strength (%)			Cells × 10^6 per cc.			
Sandy mull, pH 4.7	34.0	49.5	2.1	0.21	0.09	0.11	1.3
Earthworm crumb mull, pH 6.5	7.5	32.0	5.4	0.45	0.33	0.28	2.5
Arthropod fine mull, pH 6.5	48.4	45.1	3.7	0.30	0.01	0.07	1.7
Fen mull, pH 7.2	38.4	45.9	9.8	0.24	0.39	0.04	1.7
Arthropod bran mor, pH 5.5	27.8	22.9	20.3	0.43	0.01	0.31	4.1
Ligno-mycelial mor, pH 4.1	23.0	50.1	2.1	0.32	0.09	0.22	0.8
Moss bog mor, pH 3.9	54.0	63.3	None	0.07	0.02	0.09	0.2

The relative content of oxidizing and reducing substances, expressed in the oxidation-reduction potential of humus, indicates the general nature of microbiological processes, particularly the participation of either aerobic or anaerobic organisms. Because of the highly dynamic nature of oxidation-reduction processes, the significant values of the potential of humus can be obtained only under strictly standardized conditions of moisture and temperature (Lafond, 1950). Within broad limits, the oxidation-reduction potential is correlated with the catalytic capacity of humus material (Mikola, 1954).

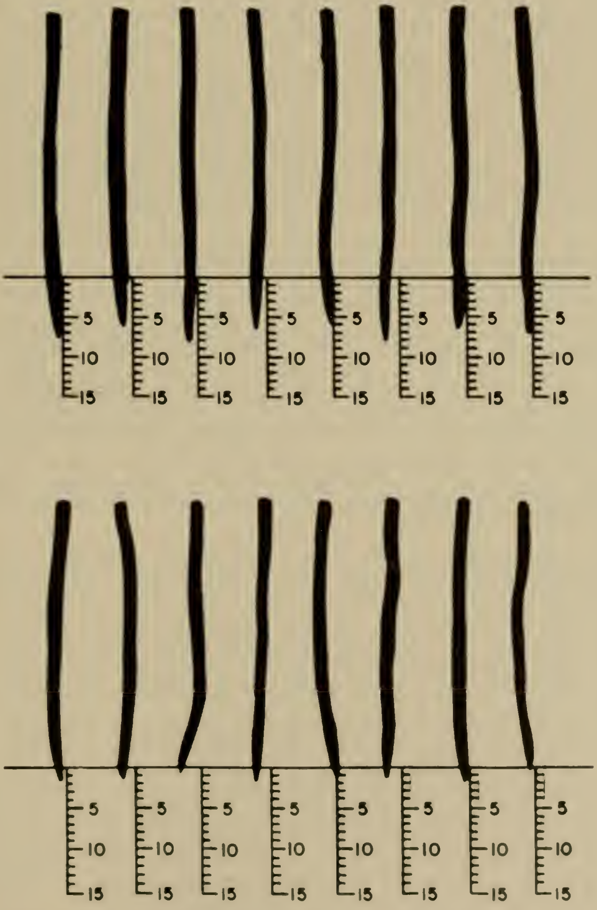


Fig. 4–6. Effect of volatile organic substances released by humus on the growth of excised roots of blue lupine. (*Top*) Average growth of 5.3 mm. produced under the influence of arthropod bran mor. (*Bottom*) Average growth of 1.8 mm. produced under the influence of saprogenous, partly lignified mor. (After Persidsky and Wilde, 1954.)

During the past few years, observations of Cholodny (1951) revealed that organic remains evolve volatile substances which exert either beneficial or depressing effects on root systems (Fig. 4–6). This phenomenon may also be used for evaluation of humus (Persidsky and Wilde, 1954; Mader, 1954).

The properties of humus layers are conveniently recorded on multigraphed forms, prepared in accordance with the analytical schedule. An example is given in Figure 4–7.

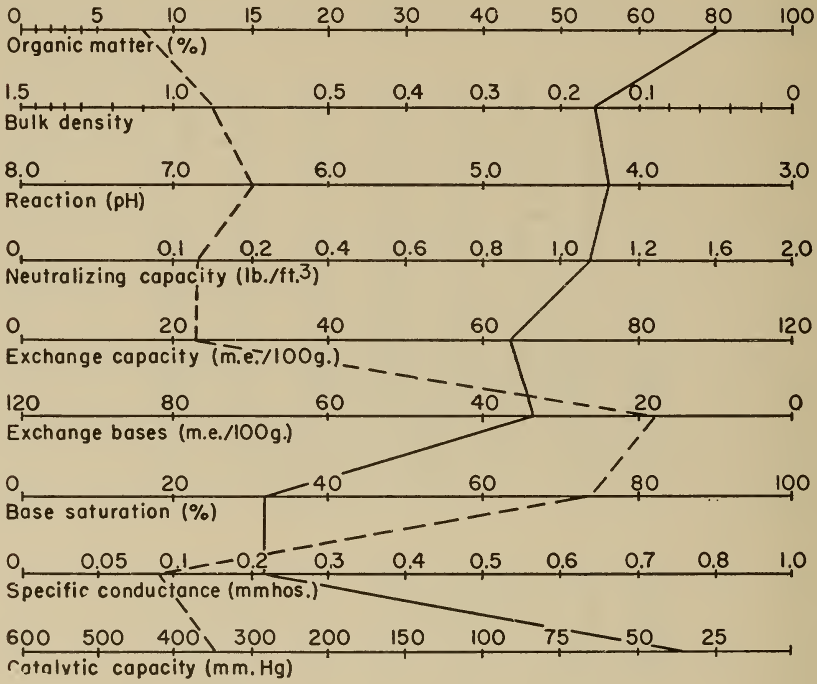


Fig. 4–7. Diagrammatic presentation of analytical results for hardwood crumb mull from the University of Wisconsin Arboretum (*broken line*), and for hemlock mycelial mor from the University of Michigan Camp Filibert Roth (*solid line*).

SILVICULTURAL IMPORTANCE OF HUMUS

The form and content of humus play an important part in the production of nursery stock, artificial reforestation, partial cuttings and natural regeneration of forest stands, vulnerability of forest stands to fire, control of floods and erosion, sustenance of wildlife, and the utilization of forest lands for agricultural purposes.

Since the earliest days of artificial reforestation, humus has served as fertilizer for nursery soils. It fulfills the same function today, being applied broadcast, as an ingredient of composts and briquettes, or in the form of suspensions (Wilde, 1946). One may question why the great progress made in the manufacture of commercial fertilizers has not eliminated the use of bulky natural organic materials which are costly to procure and awkward to handle. The reason is that certain types of humus provide a safer and better-balanced diet than do chemical fertilizers. This claim does not stem from the inherited prejudices of foresters but finds constantly increasing support in the results of investigations dealing with physiology of planting stock.

According to evidence obtained recently by the use of radioactive carbon (Snell, 1955), the photosynthetic production of carbohydrates is, under certain conditions, supplemented by the direct utilization of humus carbon. The assimilation of carbon dioxide by roots of trees endowed with mycorrhizae was also claimed by Falck and Falck (1954).

Aside from its nutritional aspects, humus is gaining recognition as a means of controlling damping-off disease, the scourge of forest nursery practice (Wilde and Hull, 1937; Leibundgut, 1950; Mikola, 1952). It is believed that pathogens are suppressed either through direct attack by certain humus-inhabiting organisms, or through nutritional, growth-promoting, and antibiotic influences of the humus material (Waksman, 1952). Recent progress in the study of antibiotics placed the subject of humus on a level of unparalleled importance, not only in regard to forest vegetation, but in regard to the health of man as well. Because of their buffering and antitoxic properties, certain types of forest humus present one of the most efficient means of counteracting the adverse effects of biocides (Mader, 1956).

The mineral portion of the soil is animated by roots of vegetation and some organisms, but changes in the composition of the soil profile below the organic layers become apparent only after scores of years, or even centuries. Humus, on the other hand, is an entity teeming with life, a dynamic system extremely sensitive to environmental conditions. In some instances even a light thinning of a forest stand by axe, wind, or destructive organisms modified the biotic equilibrium of humus (Tamm, 1950). This modification is accompanied by marked changes in the intensity of respiration, rate of nitrification, oxidation-reduction potential, and other measurable manifestations of microbiological activity. Hence, an episode in the life of mineral soil is history in the life of the humus layer.

The responsiveness of the organic horizons of forest soils to environmental changes offers an invaluable tool to silviculturists in their endeavors to create optimum conditions under the forest canopy and thus to utilize to the maximum the productive forces of the habitat. Even at the present state of silvicultural knowledge it is possible to maintain that progress toward truly scientific management of forest stands will be made through careful observation of the behavior of humus layers and their inhabitants from either the plant or animal kingdom (Romell, 1935).

It has long been known that the morphology of humus layers, particularly the thickness and structure of the ectorganic fraction, has a pronounced influence on the rate of natural forest regeneration (Morozov, 1912; Hesselman, 1926). Recent evidence has pointed out that certain concealed properties of the humus layer determine not only the rate but also the kind of natural reproduction (Lafond, 1951).

According to the agronomist's saying, "Nitrogen spells organic matter." In leached and coarse sandy soils of cut-over lands, organic matter, free or incorporated, is synonymous with the content of all nutrients and has a decisive influence on the early growth of established plantations.

One problem of paramount importance, the relationship between the form of humus and rate of forest growth, has always been and still remains a highly controversial issue.

Some Scandinavian silviculturists, following in Müller's and Darwin's footsteps, are inclined to regard mor humus as an evil and mull as a condition ideal for forest growth. They invariably refer to "good mull" and "bad mor" types, but never with a reversal of adjectives.

An American forester acquainted with the Lake States region sees the situation in an entirely different light. With few exceptions the best crumb mulls of this area occur on soils of the prairie-border transition or on poorly drained soils; such soils support inferior stands of oak and lowland hardwoods whose yields seldom exceed 10 Mbf per acre.

On the other hand, stands of white pine yielding over 30 Mbf per acre are found on soils with a forest floor of pronounced mor type. Even the worst thick mors, approaching wood peat in composition, at times support stands of white cedar and hemlock that attain 18 Mbf per acre. Consequently, on the enormous acreage of the United States the high rate of forest growth coincides with the occurrence of mor humus and leached soils (Heimburger, 1934, p. 32).

The morphology of forest layers influences the susceptibility of forest stands to fire and the fertility of burned-over soils. Mor humus ignites readily and burns persistently; soils with this form of humus lose their nitrogen through combustion and much of their available nutrients through leaching of ash constituents. Soils with mull humus, on the other hand, expose only a thin layer of litter to ground fires and are as good as immune to fertility losses.

Many recent investigations have clearly demonstrated the far-reaching role played by shriveled leaves and their leftovers in the absorption of precipitation, moderation of runoff, and control of erosion (Kittredge, 1948). In some regions the high infiltration capacity of soils that tames the raging fury of rain water is linked with the depth and crumb structure of mull layers; in other regions it is the thick mat of mor that is largely responsible for the capacity of land to prevent catastrophic floods and resist the processes of denudation.

Few foresters would care to bypass in their management plans the task of sustenance of the feather- and fur-clad members of the forest community. In many instances, the supply of game food depends upon the protection of desirable forms of humus with their associated ground-cover plants, insects, worms, and other organisms. European silvicultural experiences have demonstrated beyond any doubt that high-pressure mercantilism, which buried the natural forest floor under pure spruce plantations, achieved nothing save creation of "biological vacua" and huge financial losses.

In forest management it is not always feasible or desirable to divorce the problems of silviculture from those of agricultural land utilization. As often as not, the success of farming forest lands depends on the nature of forest humus. Mull humus usually consists of stable clay-humus aggregates and may persist for centuries even under intensive cultivation. Mor humus carries an abundant supply of energy material and decomposes in a few years after the land is cleared. This difference in the behavior of humus was dramatically revealed on a large scale in utilization of North American virgin soils. Shortly after breaking seemingly fertile soils with raw humus, the newcomers from the old agricultural regions of central Europe were faced with a sterile quartzose residue, drastically declined crop production, and, ultimately, tax delinquency. The statement of Emerson that "the first steps in agriculture . . . teach that Nature's dice are always loaded" proved to be correct.

EFFECT OF HUMUS ON SOIL DEVELOPMENT

The existing framework of soil science, nearly a century old, was largely fashioned by geologists. In accordance with their background, these students of the nonliving world visualized soil as natural body derived by weathering from the underlying substratum. The coined term "parent material" clearly indicated a picture of the soil as originated from below.

Timber growers, in their more than two hundred years of reforestation experiences, had untold opportunities to observe thin-littered and crumb-structured soils harboring earthworms, as well as leached hardpan soils covered with a thick mat of organic debris. Even though foresters failed to attribute any scientific importance to their observations, they knew that the soil originates from above, not from below, and they visualized soil in terms of "parent litter," rather than "parent substratum." These ideas were conclusively proven by Müller (1887, p. 156) who investigated the soil of an abandoned forest nursery which was homogenized by frequent cultivation and subsequently planted to spruce and oak; within less than forty years this soil produced a garden-like mull under the oak stand but a layer of raw humus and pronounced signs of podzolization under the spruce stand.

Since the time of Müller's research, the problem has been repeatedly investigated in many countries; the results of all these studies led Aaltonen (1948) to conclude that: "Mull belongs to the brownearths, raw humus to the podzol." More recent investigations of soils in tropical regions revealed that the organic fraction is responsible for the development of many genetical patterns of soils.

Following in the footsteps of dynamic geology, soil scientists concentrated their attention on the translocation of mobile soil fractions and presented soil as a profile comprising a sequence of horizons. All students of forest environment acknowledged the importance of organized soil morphology, but the geological pattern of soil did not entirely satisfy their needs. Foresters were not so much interested in the soil "profile" as in the soil "face," that is, the epidermal organic layer which plays such an important role in practical silviculture and which decides the course of soil development. This layer, however, slipped through the fingers of the founders of pedology. Not until the soil profile was divided into *A, B, C,* and later A_1, A_2, *B,* and *C,* horizons did the existence of the forest floor receive recognition as the A_0 layer or "super-solum" material (Zakharov, 1931). In truth it may be said that soil scientists did not see the soil for the horizons.

Beyond incorporation of the so-called "dead litter" into the profile of forested soils, the morphology of forest humus received no further consideration by soil scientists (Romell and Heiberg, 1931). In vain one could search through pedological textbooks for a reasonably accurate description of humus layers. Glinka (1931), one of the mainstays of pedology, failed to even mention the *A* sub-zero layer in the chapter of his book devoted to the classification of the soil profile (pp. 159–63). At present there is sufficient evidence to state that when pedologists brushed off the "dead litter" they removed with it not only the practical interests of silviculture but also the scientific foundation of soil genesis. The geologic substratum is dead and sterile; it cannot be "parent" to anything, least of all to the animated entity called soil. The genetic alterations in the biospheric portion of the earth's crust proceed under the influence of organisms and the products of their metabolism and decay (Kubiena, 1948; Wittich, 1952; Laatsch, 1954).

In this text, the genetical development of forest soils is regarded first of all as the outcome of biological activities and complex biochemical transformations which find their outward expression in the appearance and composition of humus layers.

5

The eternal genetical relationships that exist between the forces of environment and physical matter, living and non-living domains, plants and animals and man, his habits and even his psychology—these relationships comprise the very nucleus of natural science.

—V. V. Dokuchaev

Genesis of forest soils

WEATHERING AND SOIL DEVELOPMENT

Fluctuation of temperature, expansion of water on freezing, erosive action of wind and raindrops, all contribute to the rupture of rocks into "skeletal" soil material—stones and gravel. This physical weathering is usually accompanied by more profound changes caused by chemical processes such as solution, hydrolysis, carbonation, oxidation, and reduction. In chemical weathering, water, oxygen, carbon dioxide, and various acids, supplied by environment and organisms, react with minerals of the rocks and often reduce them to the size of colloidal particles. The final products of weathering include a residue of quartz and other resistant primary minerals, acids, salts, and secondary minerals, particularly hydrated alumino-silicates formed in the course of weathering (Jenny, 1941).

Weathering is primarily a geologic process which may proceed at a depth of several hundred feet, far below the sphere of root penetration. Nevertheless, weathering constitutes the initial stage of soil development and bestows upon parent soil materials properties that have decisive influence on the distribution and growth of forest vegetation. Of particular importance among the effects of weathering is the formation or destruction of clay minerals, the constituents that determine exchange capacity of the parent soil material and, in turn, the potential productivity of soils.

The composition of the products of weathering depends upon the conditions of climate and the nature of rocks. Within the boundaries of forest regions, climatic factors produce three fundamental types of weathering distinguished by radical differences in the colloidal properties of the weathered material: (1) physical disintegration, (2) sialization, and (3) feralization.

Physical disintegration is predominant in cold circumpolar regions and in high mountains. It proceeds under conditions which inhibit chemical reactions, and it climaxes in the accumulation of coarse, mineralogically unaltered debris, or even in the mere rupture of rocks. This **skeletal** or **litholitic parent material** has a negligible content of clay particles and hence a low exchange capacity. In the warm region skeletal substrata are largely confined to areas of a steep gradient and geologic formations resistant to weathering. Soils formed on skeletal parent materials support forest stands of a reasonably high rate of growth only in humid climates.

Sialization is prevalent in temperate regions and is confined to rocks whose composition includes alumino-silicate minerals. It is characterized by partial desilication of weathering products and the synthesis of secondary minerals which possess exchange properties, such as montmorillonite, hydrous mica, and kaolinite. This type of weathering climaxes in fine-textured **sialitic (Si-Al) parent materials** of high base exchange capacity. The latter characteristic is, to a large degree, responsible for the stable fertility of soils in the temperate zone. In large areas of the temperate zone, however, the development of sialitic parent materials is precluded by the occurrence of siliceous sandstones, pure limestones, chalk, and other rocks or deposits which do not contain alumino-silicate minerals. In such localities sialitic substrata are replaced by **quartzitic substrata** or **calcareous substrata.**

Feralization is confined to hot, tropical, and subtropical regions. It involves intensive hydrolysis and the disintegration of the alumino-silicate nucleus, with subsequent desilication and release of hydrated iron and aluminum oxides. Upon removal of bases and silica by percolating water, the residue largely contains insoluble iron and aluminum compounds. Such **feralitic (Fe-Al)** or **lateritic parent materials** have clay or clay loam texture but a very low exchange capacity. They often give rise to soils whose fertility can be maintained only under a permanent vegetative cover, with its periodic return of nutrients by leaf fall. Because of this, tropical agriculture is often forced to employ rotation of farm and forest crops or to give way to cultivation of perennial woody plants yielding fruits, oils, tea, coffee, spices, quinine, and rubber. Feralization is a process of utmost intensity which influences all types of rocks and deposits except those composed of quartz.

DIFFERENTIATION OF SOIL PROFILE

If conditions of climate and substratum permit the existence of forest vegetation, the parent soil material is sooner or later invaded by trees and their associates, and thus converted into a forest soil. Root systems of forest plants and a deposit of forest litter are the attributes which forest soils acquire at the very beginning of their development. These serve as the principal tools in building soil fertility. Root systems extract nutrient salts from the mineral substratum; the leaf fall returns the salts, together with photosynthetically produced carbohydrates, to the surface soil. This constant enrichment of soil in nutrients and energy material presents the initial **anabolic phase** of soil development, a process of particular importance in forest soils, with their "rotating fertility."

Under the influence of microorganisms and atmospheric agents, forest litter undergoes oxidation, hydrolysis, fermentation, leaching, and other changes. The course of this **catabolic process** and the nature of its intermediate products exert direct influence upon the morphology of the soil profile and in time transform **embryonic soils** into genetically developed or **mature soils.**

In environments favorable for the uninterrupted activity of soil organisms, the soil development proceeds under the influence of **leucinization,** a biochemical alteration that leads to the destruction of the black pigment of organic compounds. In this process the litter is rapidly broken down into carbon dioxide, ammonia, water, mineral salts, and pale-colored humates embodying colorless leucine-like amino acids and polyuronides. Catabolism of this kind is common in the warm regions of tropical forests and temperate rain forests; it gives rise to **cryptorganic soils** of various substrata. Unless soils of this group are modified by leaching or deoxidation, they indefinitely preserve their youthful appearance. However, when the forest cover is replaced by farm crops, these soils quickly reveal their true age and undergo rapid deterioration.

Where microbiological activity is interrupted by periodic droughts or freezing, the retarded decomposition of organic remains leads to an accumulation of amorphous humus, a black decay-resistant residue of lignin-like compounds which is enriched in nitrogen and possesses a high exchange capacity. In time the amorphous humus is infiltrated by percolating water or is incorporated by the activity of organisms into the upper portion of mineral soil, thereby forming a dark or **melanized horizon.** This process of **melanization,** characterized by the development of an endorganic **mull** layer, not only imparts to the surface soil a dark color but also increases the exchange capacity of the soil, its content of nutrients, and the general stability of soil fertility factors.

In many instances melanization constitutes the final as well as the initial stage of soil development and thus gives rise to a stable type of humus-incorporated or **melanized soils** of skeletal, quartzitic, sialitic, calcareous, or feralitic substrata. Morphologically, melanized soils resemble prairie soils formed by the incomplete decay of roots or grasses; occasionally they were referred to as "forest blackearths" (Schlich, 1910). In fact, some melanized soils of the forests derive the bulk of their incorporated humus from the root systems of ground cover plants and are genetically related to chernozems.

Under other conditions, the retarded decomposition of forest litter brings about the accumulation of free organic remains on the soil surface and the development of an ectorganic **mor** humus. The percolating water, reinforced with dead and living constituents of the mor layer, disrupts the stability of both the organic and mineral fractions of the soil profile. The incorporated humus as well as bases and sesquioxides of iron and aluminum are gradually leached from the upper soil layer. At a certain depth the solutions and mobile suspensions are precipitated or flocculated. As a result of this translocation of mineral and organic substances, called **podzolization,** soils display two additional layers: a **leached** or **eluvial horizon** and an **accumulative** or **illuvial horizon.** The process of podzolization may affect parent material produced by any type of weathering, with the resultant development of strongly leached **podzols** and moderately leached **podzolic soils.**

Aside from the action of percolating water, the composition of the soil profile may be influenced by the ground water. The ground water translocates soluble salts and colloids in its periodic fluctuations and causes hydrolysis and reduction of mineral and organic compounds, thus forming sticky and mottled **gley horizons.** These changes in the soil profile, called **gleization,** constitute another important process of soil development. It determines the morphology of hydromorphic soils, such as **gley cryptorganic soils, gley melanized soils,** and **gley podzolic soils** of different substrata.

On flatlands the impeded permeability of the soil may cause a prolonged saturation of the surface soil layer with free vadose water. Under such conditions, the surface, water-logged layer of the soil undergoes changes imposed by intensive hydrolysis, reduction, and the activity of anaerobic microorganisms. These processes of **surface**

gleization engender the development of **vadose soils**, which are often characterized by a light gray or grayish-tan color of surface layers. On cursory observation these soils resemble podzols and have been usually rated as podzolic, an error particularly frequent in the classification of tropical and subtropical soils (Bogatyrev, 1954). Contrary to podzolization, surface gleization is not accompanied by an increased mobility of colloids and does not lead to the formation of an accumulative *B* horizon.

Soil horizons: characteristics, designation, and importance in silviculture. Separate layers or horizons constituting the soil profile are conventionally designated by the letters *A, B, C,* and *G,* with numeric subscripts. In melanized soils the entire profile usually consists of only three layers: forest litter (A_0), horizon with incorporated humus (A_1), and parent material (C). In other soils, the profile may also include leached (A_2), accumulative (B), and gley (G) horizons. The following outline describes the designation and characteristic composition of the principal horizons encountered in profiles of forest soils.

A_0 Organic debris not incorporated with mineral soil, such as litter, duff, and raw humus. As suggested by Hesselman (1926), this **ectorganic layer** may be divided into two subhorizons: F layer (fermentation or "förna" layer), including organic remains whose origin may be detected by ocular examination; H layer (humified layer) of black amorphous organic matter whose source cannot be recognized because of advanced decomposition. The boundary between these two subhorizons, however, is not always well defined, and hence the ectorganic part of the soil at times must be designated either as F layer or FH layer.

A_1 Partly mineral, partly organic melanized horizon, produced by incorporation of amorphous humus through the activity of soil-inhabiting organisms, by infiltration of organic suspensions, or by incomplete decay of root systems. This **endorganic horizon** is dark colored and is usually high in nutrients; in most cases its composition reflects the state of soil fertility. In order to avoid the use of cumbersome numerical subscripts, this horizon can be appropriately designated by the letter *M,* referring to melanized, minero-organic, mixed, mull, or muck layer.

A_2 Leached, eluvial, or **podzolic horizon,** impoverished in soluble salts and colloids. It is commonly of a coarser texture than the underlying layer. If leaching is intensive enough to remove iron sesquioxides, the horizon is of a light color; in extreme cases it is ash-gray or white. For the reason stated above, this layer can well be designated by the letter *A* in accordance with the original scheme of Dokuchaev (1879).

A_3 A transitional zone between the impoverished (*A*) and enriched (*B*) horizons. This zone is difficult to detect in field investigations, and it has a questionable practical significance. If and when conditions call for a detailed differentiation of the soil profile, the transitional subhorizon can be appropriately marked as the *AB* layer.

B Enriched, illuvial, or **accumulative horizon**, containing precipitated soluble salts and coagulated or flocculated mineral and organic colloids. Depending upon the nature of the soil-forming process, this layer may be aggregated, compacted, or cemented and may form impervious strata, referred to as "hardpan," "ortstein," or "claypan." The color of this horizon tends to be brown or red due to the presence of ferric iron. This horizon is sometimes subdivided into B_1 and B_2, or *B*, *BB*, and *BC* subhorizons to underscore the differences in the chemical or morphological composition of the enriched zone.

C **Substratum**, exhibiting no obvious signs of alteration due to translocation of colloidal substances in the soil profile. In some cases this layer is impoverished in carbonates and soluble salts. As a general rule the mineral substratum is the parent material of soil, but it may also be of different geological origin than the surface layers of the soil. The substratum may be divided into *C* and *D* subhorizons to distinguish layers of different geologic origin. The solid bedrock may be appropriately indicated by the letter *R*.

G **Gley horizon**, formed under the influence of either phreatic or vadose water and containing ferrous iron and other reduced compounds. It is characterized either by light gray to nearly white color, or by greenish, bluish, and reddish mottling imparted by minerals in different stages of hydration; at times the mottling is masked by infiltrated organic matter. The seasonal fluctuations of ground water may produce distinct impoverished or **eluvial** and enriched or **illuvial gley layers**. The flooding of a surface soil layer with vadose water gives rise to superficial gley horizons which may contain H_2S, CH_4, NO_2^-, and other products of anaerobic decomposition. Depending on the combined effects of surface hydrolysis, melanization, and leaching, such horizons are designated as G, MG, or AG layers. The accumulation of salts in the surface layers of alkali soils and the formation of crusts of iron and aluminum oxides in feralitic soils may also be regarded as forms of gleization.

In some soils it may be necessary to include the following additional designations:

S Superficial stratum of live mosses covering peat deposits, a layer distinctly different from dead organic remains (Forsslund, 1945). Both the floristic origin and the thickness of the S layer have direct silvicultural importance.

P Layers of peat, that is, water-logged deposits of plant remains characterized by retarded decomposition and a depth usually exceeding six inches.

X Pale-colored, nitrogen-enriched horizons of cryptorganic soils.

The original system of profile classification was devised by Dokuchaev in connection with his study of chernozem soils—that is, soils comprised of *A*, *B*, and *C* horizons. When the same method was extended to forest soils, which exhibit four or more layers, they were subclassified by means of numerical symbols and the system became cumbersome. Further complications arose when Dokuchaev's scheme was applied to soils of aridic climates (Nikiforoff, 1931) and soils of tropical and equatorial regions. Numerous attempts, therefore, have been made to revise the original method, but all later proposals have met with a limited success, largely because thousands

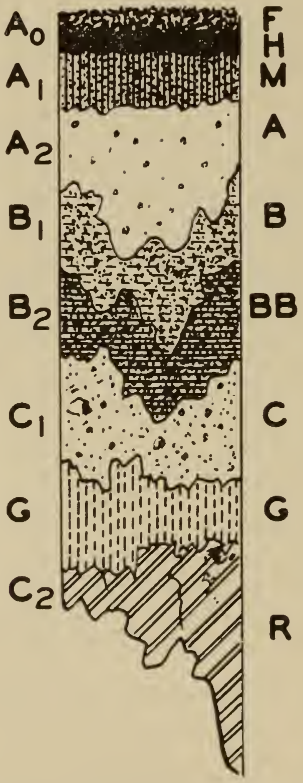


Fig. 5-1. Designation of horizons in the profile of a leached forest soil influenced by ground water. The column on the left presents the generally accepted designation of soil horizons; the column on the right presents a simplified version of the designation, eliminating subscripts.

of previously published reports described soil profiles in terms of the original designation. Moreover, the Dokuchaev designation, although awkward at times, reflects the inherent sequence of soil development and has a more logical basis than purely empirical schemes. Consequently, an attempt is made in this text to preserve the original Dokuchaev pattern but to eliminate the numeric subscripts which unnecessarily complicate typing and printing of soil descriptions. Figure 5–1 illustrates the designation of horizons in a profile of a leached forest soil influenced by ground water according to the generally accepted system and its simplified version.

The boundaries of soil horizons seldom follow a horizontal or a straight line; rather they form an irregular, undulating, or even a zigzagging contour. Therefore, in the descriptions of soil profiles or in schematic drawings it is desirable to indicate the minimum and the maximum depth of the soil horizons and their general outline.

The recording of soil horizons is important, not only in the genetical studies of soil, but in practical silviculture as well. The composition of forest stands, their rate of growth, the possibilities of natural reproduction, and silvicultural management are intimately dependent upon the amount of raw organic remains, depth of incorporated humus, composition of the leached and accumulative layers, nature of parent material, and the proximity of the gley horizon. Comparable data cannot always be obtained if the composition of separate soil layers is disregarded in physical, chemical, and microbiological soil analyses.

SOIL AS A FUNCTION OF ENVIRONMENTAL FACTORS AND TIME

The first basic law of soil science, formulated by Dokuchaev, states: "The soil is a result of reactions and reciprocal influences of parent rock, climate, topography, plants, animals, and age of the land." Mathematically speaking, the soil (S) is a function of geological substratum (g), environmental influences (e), biological activity (b), and time (t):

$$S = \int (geb)\,dt$$

Although the discussion of soil development must be subdivided into climatic, topographic, geologic, and biotic aspects, no such division exists in nature. Therefore, the classification of soil on the basis of climate or any other single factor, no matter how influential, has only a general or a schematic significance. This is especially true in dealing with forest soils. The forest itself is a factor of tremendous modifying power; it may bring podzolization into a region of prairie or lateritic soils; vice versa, it may arrest the leaching and promote the blackearth-like process of humus incorporation in the heart of the podzol or laterite region.

Relation of soils to climate. Climatic factors exert profound influence on the distribution of plants and the development of soils. As a result, soils of different morphological patterns are arranged on the globe in broad zones correlative with vegetational zones. Some of these zones form continuous belts across entire continents; others occur as large islands.

A certain minimum amount of total heat is one of the prerequisites for the existence of forests and hence for the occurrence of forest soils. In arctic regions and high mountains, where the average temperature of the growing season is below 50° F., the forest is replaced by lichens, mosses, and heath shrubs (Mayr, 1909). The soils of such microthermal environments include **skeletal barrens, tundra** or **muskeg** soils, and **alpine meadow** soils. Of equal importance to forest existence is the humidity of the climate, an appreciable excess of precipitation over evaporation (Hilgard, 1892; Meyer, 1926). In arid and semiarid climates, the vegetative cover consists of grasses, xerophytic shrubs, cacti, and halophytic plants inhabiting **blackearths** or **chernozems**, other **grassland soils, desert soils,** and **alkali** soils. The general tendency of these nonforest soils is to accumulate salts in their surface layers through either the action of plants or evaporation and recrystallization from solution.

In the regions conducive to the growth of forest vegetation, the composition of forest cover and the course of soil development depend upon the amount and distribution of rainfall as well as the state of temperature (Ramann, 1918).

The cold portion of the humid region is correlated with the occurrence of the boreal, largely coniferous forest, and with the predominance of **podzol** soils. Near the warmer boundary of the podzol zone, the conifers are mixed with broad-leaved species; accordingly, the true podzols are largely replaced by less strongly leached **podzolic soils.** The northern hardwood-coniferous forest is usually separated from steppes and prairies by a wide belt of sporadic stands of oak and associated deciduous species. The nut-structured **prairie-forest soils** or **grood soils** of this transitional zone exhibit characteristics of both prairie and podzolic soils. The podzolized soils and the prairie-forest soils develop in the regions with lasting snow cover and have one common characteristic: the accumulative *B* horizon enriched in iron and aluminum sesquioxides. Therefore, in a broad classification, they may be united in the same family of **endoferalic soils.**

In the warm environment of the tropical forests, soils develop, by and large, on feralitic parent materials impoverished in silica but enriched in iron and aluminum oxides. In regions of abundant, continuous, or periodic rainfall, occupied by rain forests and monsoon forests, the predominant morphological varieties of soils are **cryptorganic feralites** or **redearths, melanized feralites,** and **podzolized feralites.** In some localities, however, there occur various soils of sialitic substrata, and even **tropical podzols** similar to those of the boreal forests. The entire area of tropical and temperate rain forest is dotted with **cryptorganic sialites.** Large areas of the tropic remain submerged during the rainy season and, under the influence of surface gleization, develop **vadose soils** of either feralitic or sialitic substrata. With extended periods of drought, the monsoon forest is replaced by parklike savannah forest and scraggly thorn forest. These picturesque formations often exist on humus-impoverished, **indurated redearths** or **laterites.** The laterites present the end product of feralitic weathering and in the extreme stages of development form thick stonelike crusts of iron and aluminum oxides. The peri-

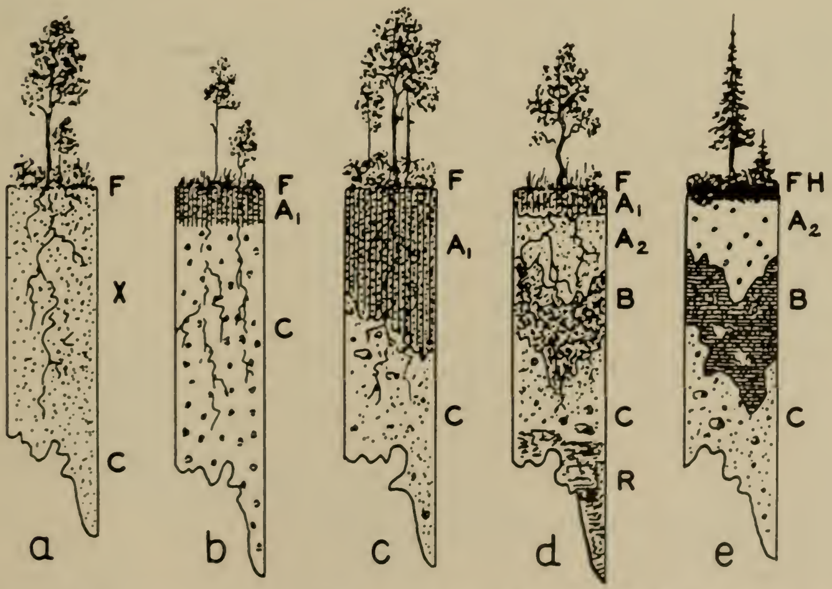


FIG. 5-2. Profile features of mature forest soils belonging to different genetic patterns: (*a*) cryptorganic silt loam; (*b*) melanized siliceous sand; (*c*) melanized loam; (*d*) podzolized soil of a calcareous substratum; (*e*) sandy podzol with hardpan horizon.

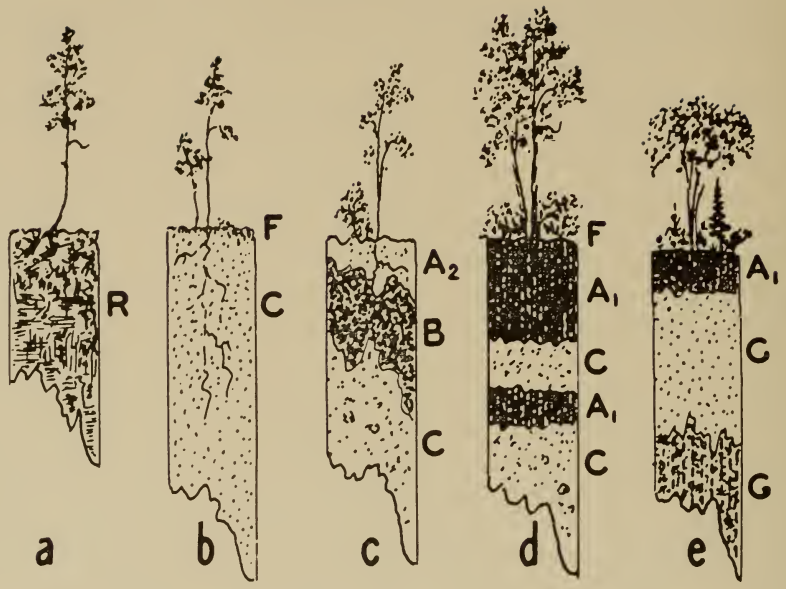


FIG. 5–3. Profiles of representative embryonic soils: (*a*) slightly weathered rock outcrops; (*b*) windblown sand; (*c*) eroded loam lacking humus-enriched layer; (*d*) overwash loam with buried humus horizon; (*e*) alluvial sand of stream bottom.

odically dry littoral districts adjacent to tropics are occupied by sclerophyl or leatherleaf forests growing on moderately feralized, reddish-brown **littoritic** or **charral soils** (Wilde, 1946).

In an oceanic climate the hardwood-coniferous forests and the evergreen subtropical forests are separated by irregular belts of mesophytic hardwoods, such as "central hardwoods" of America and the "Fagetum" association of Europe. These forests occupy the meeting ground of the two major processes of forest soils development: podzolization, leading to the impoverishment of the surface soil layers in sesquioxides; and feralization, producing an enrichment of the surface layers in the same compounds. The mutual neutralization of these two diametrically opposed processes results in the development of **cryptorganic sialites** and **melanized sialitic soils** whose silica and sesquioxide compounds preserve their stability in the entire profile. The melanized sialites in European literature are usually referred to as **brownearth soils.**

Figure 5–2 illustrates schematically the morphology of genetically developed upland forest soils.

Because of the ceaseless dynamic processes of the earth, genetically mature soils of all climatic regions are dotted with denuded areas and youthful deposits of fluvial, aeolian, volcanic, and gravitational origin. Some of these **embryonic** or **primitive soils** have a very low fertility; frequently they are a curse brought on man by his misuse of the land. Other soils of this group are a blessing, for they carry an abundant supply of nutrients and colloids derived from the surrounding hills or from deep strata of the earth. Figure 5–3 outlines profile features of widely distributed embryonic soils.

The study of mountain soils by Dokuchaev (1899) revealed that the soil zones succeed each other in a definite order with the increase in altitude. This **vertical zonality** of mountain soils is analogous to the **horizontal zonality** found on the plains. A particularly striking illustration of the parallelism between horizontal and vertical zonalities of soils is presented by European Russia. The Great Russian Plain extends from the Arctic Circle to the Caucasian Mountains. This territory, from north to south and from sea level to its highest altitude, exhibits a wide range of climates and soil conditions (Fig. 5–4). The Rocky Mountains (Thorp, 1931; Pearson, 1931), as well as the other mountain ranges of the United States, present similar examples of the vertical zonality of soils.

An instructive picture of vertical zonality of forest soils in the Alps of northern Italy was recorded by Jenny (1930):

Altitude (meters)	*Soil Group*
100– 200	**Yellowearths and redearths**, largely iron-enriched soils of moraines.
200– 700	**Brownearths**, partly replaced by humus-calcareous soils or **rendzinas**.
700–1700	**Podzol soils**, including both strongly and weakly podzolized varieties.
1700–2700	**Alpine humus soils**, sometimes only a few inches deep.
2700–3500	**Skeletal soils**, grading into a zone of ice and snow.

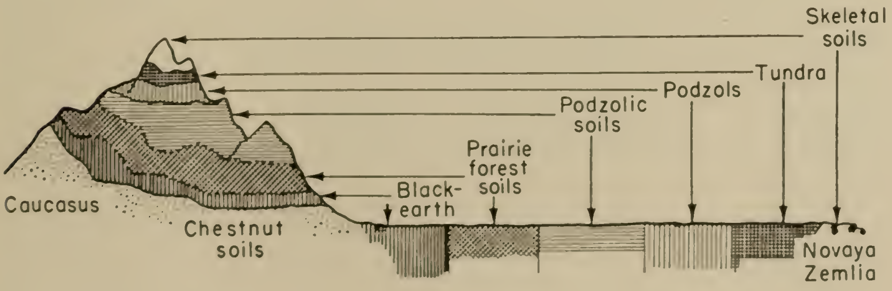


FIG. 5–4. Relation between the horizontal and vertical zonality of soils in European Russia. (Adapted from Zakharov, 1931.)

The occurrence of different zonal types in the mountains is greatly affected by the geographical location of the range and by exposure. The differentiation of horizons is less pronounced in the mountains than on the plains because of continuous erosion and deposition. The deep and more fertile soils of overwash are often intersected by the shallow and less productive residual soils of denuded areas, or by rock outcrops. The presence of rock fragments is characteristic, especially at high altitudes where mere physical weathering produces skeletal or litholitic parent materials. The **mountain podzols** and **alpine sward soils** formed on such substrata support species of spruce, pine, fir, larch, and a few other microthermic tree species that struggle against the severe environment similar to that of the arctic lands.

Figure 5–5 presents schematically the distribution of the major soil units in relation to temperature and moisture.

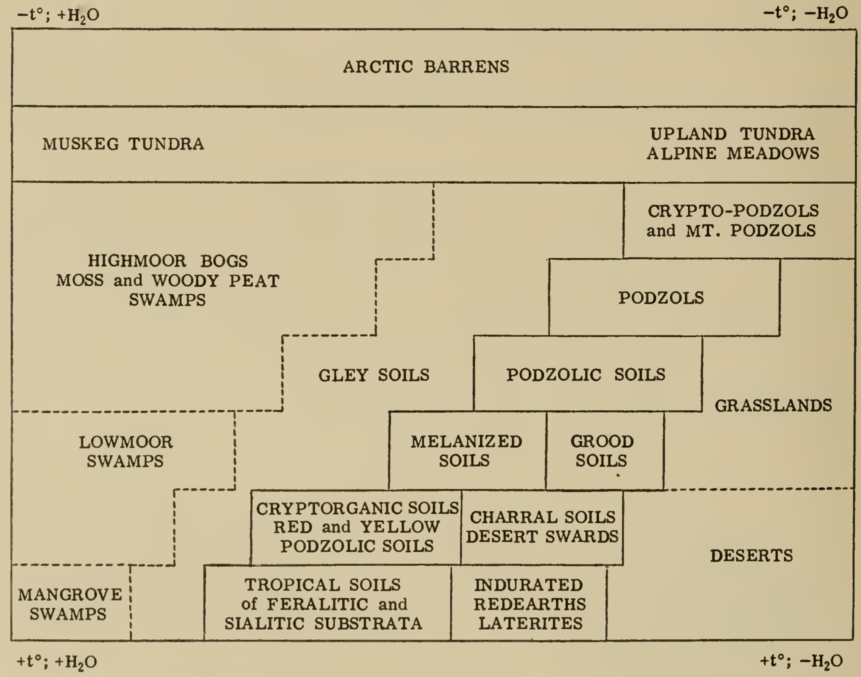

−t°; +H_2O
−t°; −H_2O
ARCTIC BARRENS
MUSKEG TUNDRA
UPLAND TUNDRA ALPINE MEADOWS
CRYPTO-PODZOLS and MT. PODZOLS
HIGHMOOR BOGS MOSS and WOODY PEAT SWAMPS
PODZOLS
GLEY SOILS
PODZOLIC SOILS
GRASSLANDS
LOWMOOR SWAMPS
MELANIZED SOILS
GROOD SOILS
CRYPTORGANIC SOILS RED and YELLOW PODZOLIC SOILS
CHARRAL SOILS DESERT SWARDS
DESERTS
MANGROVE SWAMPS
TROPICAL SOILS of FERALITIC and SIALITIC SUBSTRATA
INDURATED REDEARTHS LATERITES
+t°; +H_2O
+t°; −H_2O

FIG. 5–5. Schematic outline of the distribution of soils in relation to temperature and moisture.

The disclosure of the climatic-zonal pattern of the earth contributed greatly toward the understanding of the nature of soils. It changed the concept of soil as a mere accidental mixture of mineral and organic matter to that of a unique entity which forms under the influence of external factors and which in advanced stages of development serves as a mirror of environment. The recognition of soil as a geographic phenomenon helped to consolidate the fragmentary information on soils into an organically welded body of knowledge that eventually attained the recognition of a separate scientific discipline.

In serving the interests of silviculture, climatic-zonal classification of soils provides a natural framework for acclimatization or naturalization of foreign tree species. It facilitates the correct evaluation of the effects of different ecological factors and prevents the gross errors made by indiscriminate translocation of foreign silvicultural techniques to unsuitable environments.

At the same time, the climatic **macrozonality** of soils must be regarded in terms of a broad general scheme not designed to meet the needs of current silvicultural practice. As stressed by Sibirtzev (1901), the climatic soil regions represent the prevailing *tendencies* in soil development, not concrete classificational units. Within each climatic-vegetational zone the influence of local soil-forming factors gives rise to a range of morphological varieties of soils that have decisive practical importance. In many instances, such varieties exhibit morphology essentially different from that of the zonal soils and hence form intrazonal intrusions. The wide distribution of melanized soils in the podzol region and the occurrence of podzolized soils in the region of prairie-forest soils are examples. Therefore, in soil classifications related to silvicultural management, the primary emphasis must be placed on the **microzonality** of soils determined by topographic features, position of the ground water table, nature of parent soil material, age of soil, and composition of forest cover.

Soil-forming role of topography. The knowledge of the influence of topography on the composition of soils is literally "as old as the hills." Topography serves as a multifaceted prism dispersing or concentrating the effects of climatic factors. It directs the course of runoff water and determines the relative content of soil moisture, the depth to the ground water table, and the distribution of erosion products—soluble salts, mineral colloids, and organic matter. All of these conditions in turn exert a profound influence on the composition of vegetative cover and the morphology of the soil profile. An example from the prairie-forest transition of the American Midwest should suffice to illustrate the effect of topography on the composition of soil (Fig. 5–6).

The flat portions of limestone ridges for many centuries supported tall prairie grasses and developed dark prairie soils with a high humus content. On the upper slopes of northern exposure the lasting

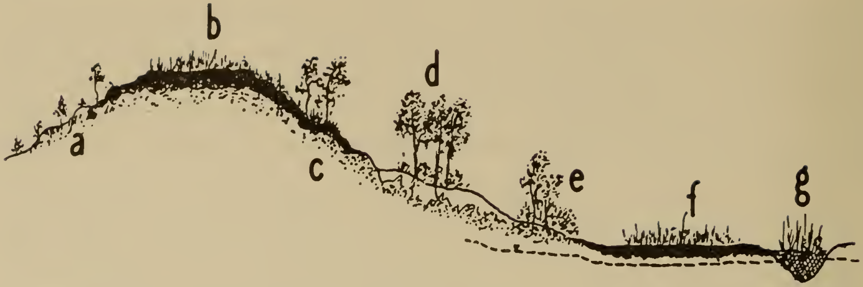


Fig. 5-6. Distribution of genetic soil types in relation to topography in the prairie-forest transition: (*a*) shallow calcareous regolith with outcrops of limestone (southern exposure); (*b*) prairie soil; (*c*) dark prairie-forest loam; (*d*) leached prairie-forest loam; (*e*) gley loam; (*f*) lowland prairie soil; (*g*) sedge peat.

snow cover permitted scattered bur oaks and other pioneer trees to challenge the domination of prairie plants. This vanguard of the forest maintains a foothold under the stress of grass competition on dark prairie-forest soils only slightly altered by the effects of tree roots and forest litter. With the increase in moisture content on the lower slopes, forest stands attain full stocking and a higher rate of growth. At the same time, the soil undergoes leaching and exhibits a gray eluvial layer and a nut-structured accumulative horizon enriched in sesquioxides. At the foot of the hill, the soil is underlain by ground water whose presence is manifested by a discolored and mottled gley horizon. With the approach of the ground water table to the surface, the impeded aeration precludes the existence of trees and the land is taken over by sedges and other hydrophytic plants. These develop lowland prairie soils with a black sapropel-like surface layer underlain by mottled waterlogged substratum. Besides the poor aeration, the invasion of marsh vegetation in the lowlands is induced by accumulation of carbonates. The stagnant depressions or "kettle holes" are filled with sedge peat formed by partly decomposed remains of marsh vegetation. The sun-scorched southern and western exposures are denuded by climatic influences as well as by grazing of animals, first wild and then domestic. The shallow melanized regolith of these sites supports scanty cover of grasses dotted with red cedar and occasionally perforated with outcrops of limestone.

Hydromorphic patterns of soil development. The proximity of ground water is responsible for the occurrence of hydromorphic soils, which include two more or less distinct groups: **gley soils** and **organic** or **peat soils.** The latter group is usually characterized by accumulation of raw organic remains in layers exceeding six inches (Fig. 5-7).

Gley soils are classified on the basis of the morphology of their surface layers into **gley melanized, gley podzolic,** and **gley feralitic soils,** or other types. In detailed classifications each of these types is subdivided according to the position of the waterlogged layer into **surface gley** or **vadose soils,** and **shallow-gley, mid-gley,** and **deep-gley soils.**

Organic soils developed under the influence of subterranean water are called **lowmoor soils,** whereas those formed under conditions of high atmospheric humidity and vadose water are called **highmoor soils.** Depending upon the botanical origin of their surface layers, organic soils are further classified as **sedge peat, moss peat, wood peat,** *Hypnum* or **brown moss peat,** *Sphagnum* or **green moss peat,** and other types.

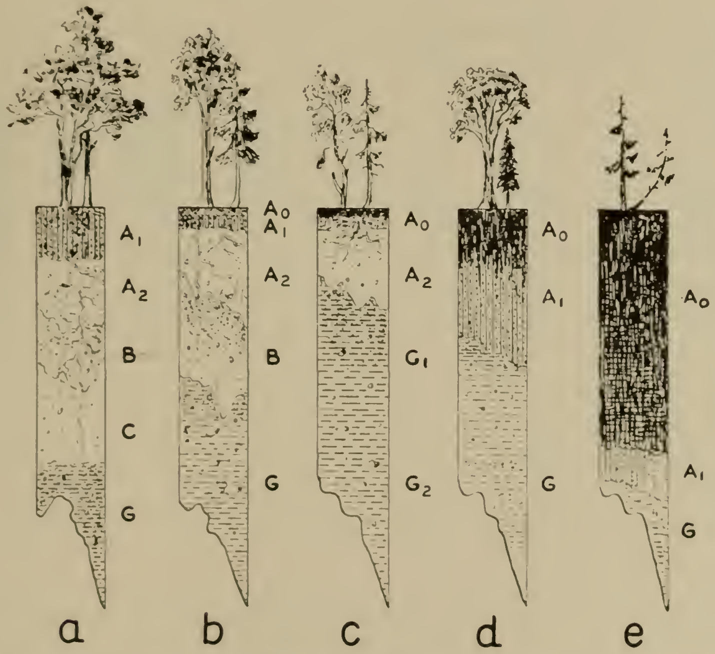


FIG. 5-7. Representative profiles of hydromorphic soils formed under the influence of ground-water: (*a*) melanized deep gley loam; (*b*) podzolic mid-gley loam; (*c*) shallow-gley loam podzol; (*d*) lowmoor sapropel-like muck soil formed in an area subject to inundation; (*e*) highmoor peat soil derived from bog moss.

Influence of parent material on soil formation. The effect of the parent rock or other parent material on physical and chemical properties of soils is subject to wide variation. The soil profiles which develop under unbalanced or extreme climatic conditions are influenced by the parent material only to a limited extent. The surface mineral layers of mature podzols consist of pure silica regardless of the nature of the parent material. Similarly, on most substrata the upper layers of true laterites are composed of iron and aluminum oxides. On the other hand, soils occurring in regions with a mild climate, such as melanized and weakly podzolized soils, preserve many important properties acquired from their parent rocks, as was pointed out long ago by Fallou (1862).

Calcareous rocks and deposits exert the most pronounced and lasting influence upon the soil. Their high content of carbonates tends to maintain the original alkaline reaction and inhibits the leaching of salts and colloids. As a result, parent materials of calcareous origin develop in many climatic zones melanized soils with a deep layer of incorporated humus, called **rendzinas.** In cold and humid climates, calcareous rocks develop, besides these **endorganic rendzinas, ectorganic rendzinas** covered with a thick layer of alkaline raw humus (Galloway, 1941). Because an alkaline reaction favors the growth of grasses rather than trees, calcareous rocks and deposits at times give rise to **prairie soils** within the region of podzolic soils. The occurrence of such blackearths without the horizon of lime accumulation is especially common near the boundary of chernozems. **Terra rossa** is a variety of soils derived from calcareous substrata in the region of lateritic weathering (Blanck, 1930). Basic or ferromagnesian rocks behave more or less similarly to calcareous parent materials. In mild climate and under hardwood stands, basalt, andesite, and similar rocks often develop into soils resembling rendzinas or humus-calcareous soils. In general, however, the resistance of ferromagnesian parent material to leaching is considerably lower than that of limestone. The siliceous rocks, especially sandstones, are influenced by environmental conditions to a comparatively lesser degree because of the inert nature of silica. The granitic rocks produce in different climatic regions soils of a wide range of profile morphology.

The influence of parent material in different climates can be best illustrated by a comparison of mature soils which have developed on limestone, sandstone, and granitic substrata in the podzol, chernozem, and transitional prairie-forest regions (Fig. 5–8).

In the semiarid region occupied by prairie grasses, blackearths or chernozem soils develop on all three types of rocks. The blackearths derived from limestone rocks (L) have more bases and a higher content of humus than soils derived from granitic (G) and especially from sandstone (S) rocks. In the podzol region, podzols or podzolic soils are formed also on all types of rocks. The soils of granitic parent material show the leaching and other features of podzolization most sharply. The soils of siliceous origin are low in mineral colloids and often manifest the effects of podzolization to a somewhat lesser extent; occasionally, such soils are too dry to support podzol-forming species and escape podzolization. The soils derived from limestone resist leaching and usually retain bases in the lower part of the soil profile. In the prairie-forest transition, calcareous rocks or loessial deposits frequently produce chernozemlike prairie soils, whereas granitic rocks give rise to podzolic forest soils. The sandstone soils, owing to their coarse texture and deficiency of nutrients, support either stands of pioneer trees or a stunted cover of prairie grasses. In either case these soils develop a thin melanized layer but no other profile characteristics.

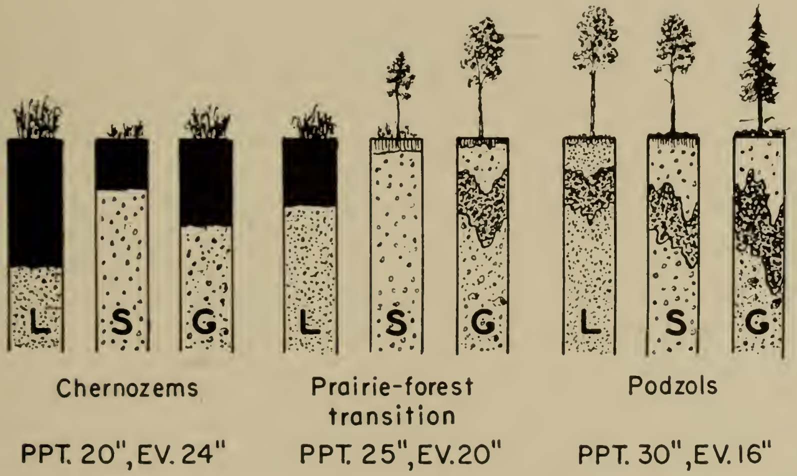


FIG. 5-8. Influence of limestone (*L*), sandstone (*S*), and granitic (*G*) parent materials upon the development of soil profiles in different climatic regions (schematic presentation).

Biotic factors of soil development. Well-stocked forest stands appreciably modify the temperature and the moisture content of the soil. The effect on soil moisture is particularly important, as the trees influence not only the amount of precipitation that reaches the ground and percolates through the soil but also the position of the ground water table. Different types of forest cover are known to affect porosity, aeration, and permeability of soil (Němec and Kvapil, 1925). The roots of trees and ground-cover plants produce various amounts of carbon dioxide, which increases the solubility of carbonates, phosphates, and silicates. During the growing season leaves accumulate nitrogen, calcium, magnesium, potassium, phosphorus, sulfur, iron, and other elements. The content of accumulated salts varies greatly with the species, but shade-tolerant trees, such as maple, beech, basswood, spruce, and fir, accumulate considerably higher amounts of nutrients than do light-demanding species, such as aspen, paper birch, and jack pine. Simultaneously, leaves synthesize widely different organic compounds whose structure determines the base exchange capacity of litter and its content of free basic or acidic constituents, carbon-nitrogen ratio, availability of nitrogen, and relative resistance to decay (Waksman, 1938). When the leaves are deposited on the ground, their physical and chemical composition plays a significant part in the multiplication of different groups of humus-forming organisms, the development of the humus horizon, and, in turn, the entire soil profile.

The litter of most deciduous species tends to undergo rapid decomposition and to retard the process of podzolization. On the other hand, the litter of most coniferous species is less vulnerable to decay and, in an environment not favorable to microbiological activity, generates strong reducing agents which encourage the process of podzolization. As a rule, these effects of trees are reenforced by the remains of associated ground-cover plants.

No matter how strong is the soil-forming influence of forest vegetation, it may be offset by the more powerful effects of climate, topography, and parent rock. Because of this, melanized or weakly podzolized soils are often found under coniferous stands, whereas strongly leached and cemented podzols are formed under stands of deciduous species.

The properties of forest litter gave rise to the classification of trees into "soil-improving" and "soil-deteriorating" or "podzol-forming" species. Such a classification should be accepted with certain reservations. The process of podzolization is not necessarily synonymous with the deterioration of forest soil fertility; in numerous instances the contrary is true.

In some earlier writings the "soil-deteriorating" or "soil-conserving" effects of litter were ascribed to differences in its content of bases. The influence of forest litter embraces complicated physicochemical and biological reactions in which the bases play only a subordinate role; litter of spruce, hemlock, and other podzol-formers often has the same content of bases and other nutrients as the litter of distinct soil-conserving species, such as beech, hard maple, or basswood. The work of Leiningen (1931) contains a review of many reports dealing with this relationship. The various aspects of forest influences are treated by Kittredge (1948).

Soil as a dynamic entity. In the course of time the soil undergoes manifold changes. In a genetical sense, the soil originates as a form-less "embryonic" deposit; it attains "maturity" when its profile shows distinct horizons; and under the influence of denudation, laterization, podzolization, swamp formation or paludization, and other processes it may pass into a state of deterioration or "senility."

Aside from the comparatively slow evolution of the soil profile, the physico-chemical composition of the soil body exhibits marked annual and seasonal changes. Foresters who are engaged in reforestation and who have the satisfaction of observing the successful growth of plantations are well aware of the time element in soil development. Under the protection of an established forest canopy, the depleted soil of burned-over barrens often regains its normal appearance and much of its fertility within the brief period of 20 to 30 years. The effect of soil dynamics is still more obvious to a silviculturist in charge of a permanent nursery. In many instances the chemical composition of the soil in such nurseries can be maintained only with the help of two or three applications of fertilizers each year.

6

We must remember that a classification is only a temporary structure, which not only can, but must, undergo changes in accordance with the growth of factual knowledge.
—K. D. Glinka, 1931

Upland forest soil groups

From a pedogenetical viewpoint the upland soils supporting forest cover fall into two age categories: (1) **embryonic soils,** which because of their insufficient weathering, recent origin, or instability do not bear the imprints of environmental influences; (2) **mature soils,** which have remained stationary for a sufficiently long time to reflect the effect of environmental factors by a differentiation of their profiles into genetic horizons.

EMBRYONIC SOILS

The terms "embryonic soils," "immature soils," and "primitive soils" are applicable to earth's strata in the initial stages of weathering and to recent deposits of colluvial, aeolian, and fluvial origin. Rock outcrops, boulder pavements, stony or gravelly debris of talus slopes, wind-blown and beach sands, substrata exposed by denudation, overwash of eroded material, beds of burned-out peat, and various deposits of streams are the major representatives of embryonic soils.

Invasion of forest vegetation covers the exposed mineral material with a blanket of litter. If circumstances permit, the surface layer eventually becomes enriched in amorphous humus, derived either from the decomposed organic remains or brought from surrounding uplands. Deposits underlain by ground water, regardless of their age, exhibit a deoxidized, discolored, or mottled zone—the gley horizon. In time, embryonic soils may attain maturity by forming a sequence of genetic horizons. This, however, is often prevented by insufficient weathering, a continuous denudation of the surface layer, or a deposition of material eroded in the upper portions of the topography. In some instances, foresters must take upon themselves the role of a "soil-forming factor" and encourage, by different cultural means, the stabilization of embryonic soils and their conversion into soils of normally developed profiles.

By and large, embryonic soils are "problem lands" for a farmer as well as an orthodox pedologist. The originators of soil classifications usually regarded these soils as "geographic misfits" which disrupt the unity of climatic-zonal classificational patterns. As a rule, these pariahs of pedology were dismissed with the dubious designations of "deposits," "soils with imperfectly developed profiles," "azonal soils," or even "abnormal soils."

Foresters visualize embryonic soils in an entirely different light. These soils have a simple morphology, and their designation does not require the use of artificial, often questionable terminology. They occur in all climatic provinces and exhibit an extremely wide range of productive capacity, supporting dwarf trees that clasp rock outcrops and magnificent stands nourished by humus-enriched overwash or recent deposits of volcanic ashes. Within this range of productivity embryonic soils reflect, in a conspicuous manner, the effect of the three major soil factors influencing forest growth—water, aeration, and nutrients. It seems as though the group of embryonic soils was designed by nature to demonstrate on simple examples the basic relationships between the soil and forest growth—relationships which are often obscured by the complexity of mature soils.

The following discussion of embryonic soils is limited to the types of major silvicultural importance. Fig. 6–1 includes typical profiles of these soils.

Rock outcrop soils. Within forest regions the occurrence of rock outcrops is limited largely to high mountains, steep slopes, and areas denuded by the action of glaciers. No other plant-bearing strata illustrate better the modifying force of climatic factors than do rock outcrops. In the regions deficient in rainfall it has been an accepted axiom that seed fallen on barren rock is doomed to perish. This is far from the truth in the humid environment of boreal lands, where not only level but even nearly perpendicular outcrops of granite and schists are covered with dense forest stands. The nutrition of trees on these sites presents an extreme example of "solid phase feeding," a direct assimilation of nutrients from minerals with a minimum uptake from soil solution or buffering colloids. Nutrition of this type can be accomplished only with the help of symbiotic fungi. Trees on rock outcrops satisfy their moisture requirements largely by utilizing water condensed on the cool surfaces of fissures.

Under favorable conditions rock outcrops provide habitat for trees of considerable moisture and nutrient requirements, such as white pine, hemlock, and spruce. In dry climates they support less exacting, drought-resistant species, particularly pines. Several mensuration studies have shown that trees on exposed rocks at times grow better than on coarse outwash sands of the same petrographic composition (Wilde, Wilson, and White, 1949).

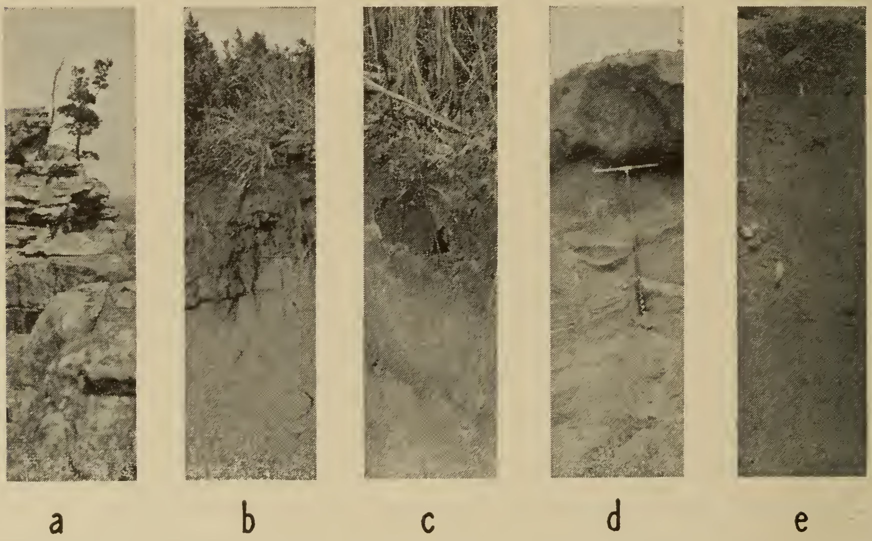


Fig. 6–1. Profiles of embryonic or primitive forest soils: (*a*) rock outcrop soil in initial stages of development; (*b*) wind-blown sand; (*c*) stream-bottom, alluvial sand influenced by ground water; (*d*) leached soil of calcareous pitted outwash decapitated by erosion; (*e*) highly fertile overwash loam enriched in humus.

Stony and gravelly soils. The coarse colluvial detritus of talus slopes, cliff debris, and avalanches in some localities impart to the countryside a distinct beauty; in others they appear as wounds on the face of the earth and must be healed by foresters at a very high cost. Sometimes colluvial deposits endanger transportation, and their stabilization requires work of both engineers and tree planters. The caprice of glaciation has in some cases produced extensive areas of so-called "boulder pavements," whose designation is not entirely metaphoric, for these coarse, indurated deposits resemble the premacadam types of European highways. In close ecological relation with "boulder pavements" are "snake mounds," winding, gravelly ridges of eskers.

The piles of coarse rock fragments usually are similar to rock outcrops in their supply of available water and nutrients. Yet, skeletal material allows deeper penetration of tree roots and accumulation of the fine earth and organic matter in crevices and fissures. A greater stability of stands and subsequent closer density of canopy permit the existence of some herbaceous plants and low shrubs. The resulting increased leaf fall from the main stand and the understory contributes to soil fertility and accelerates the growth of trees.

The value of stony and gravelly deposits decreases with the aridity of climate; outside of the humid region such soils support largely drought-resistant pioneer species or scrubby chaparral stands.

Aeolian or wind-blown sands. The erosive action of wind and the formation of sand dunes proceeded ceaselessly for many thousands of years. This type of erosion was particularly prominent immediately after glaciation and caused the burial of large areas under traveling mounds of aeolian sands (Fig. 6–2). In humid regions pioneer forest vegetation arrested the movement of sands, but only in rare instances converted them into reasonably productive forest soils.

The profile of wind-blown sands consists of a thin layer of litter and a substratum of coarse, peculiarly stratified siliceous sand. A

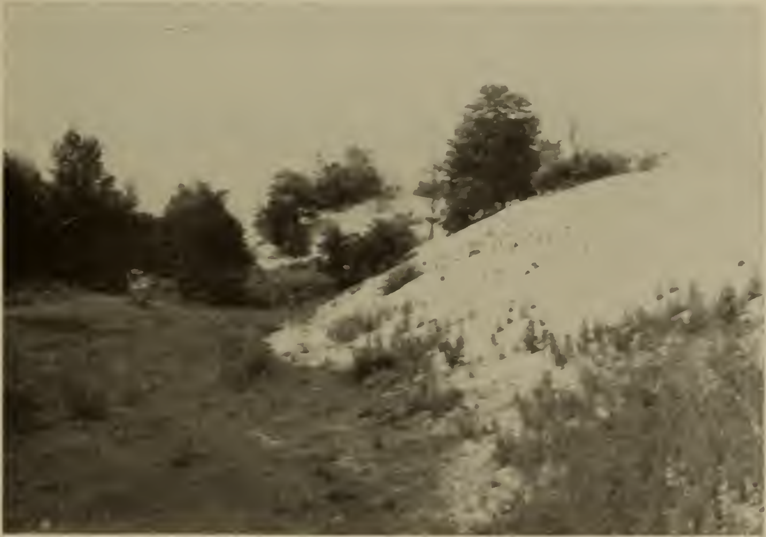


FIG. 6–2. An active sand dune supporting sporadic cover of pines and red cedar, an unstable equilibrium between the two basic pedological concepts—"soil" and "deposit." (Wisconsin Conservation Department.)

thin layer with incorporated humus occurs infrequently. The content of mineral colloids is practically nil, and the content of organic matter in the upper 6-inch layer seldom exceeds 0.7 per cent. Soil reaction usually ranges from pH 5.0 to pH 7.0, although sand dunes enriched in calcareous material with a reaction of pH 8.0 are found occasionally.

The growth of trees on these soils is handicapped by both the deficiency of water and the low content of nutrients. In continental climates wind-blown sands support pioneer pines, juniper, red cedars, and struggling scrub oak. Shrubs are usually absent, and the ground cover is formed by snow white blankets of reindeer moss, other lichens, and xerophytic grasses. The stands have a low density and yield only a few cords per acre. Because of the absence of game food plants, some specialists regard wind-blown sands as "islands of biological desert." In fog belts of water basins the growth conditions are more favorable, and in places, sand dunes develop into productive podzolic soils supporting exacting tree species.

Beach sands. Beach sands, sand bars, sand spits, and similar deposits occupy a considerable total area skirting the shores of seas and lakes. Upon superficial examination these water-laid soils resemble wind-blown sands. Nevertheless, the ecological aspects of these two types are essentially different. Because of the proximity of the ground water table, beach sands often support forests of diversified composition and a fair rate of growth (Fig. 6–3). The fertilizing effect of ground water, infiltrating humate suspensions and salts in solution, is a contributing factor of considerable importance. By and large, the forest cover of beach sands is composed of pines, but almost any other native tree species, coniferous or deciduous, can be found on this soil type.

Drained and burned-out peat soils. Artificial drainage of peat and subsequent fires have left in certain parts of the United States large tracts of land which have no place in either the natural system of soil classification or in the common pattern of land use. The mineral gley substratum, exposed by fire, was for centuries under the influence of ground water charged with so-called "ulminic" acids, and is deficient in essential nutrients. In some instances, analyses of such hydrolyzed soils revealed only a small fraction of one part per million of boron and manganese. As the result of this unparalleled paucity of nutrients, volunteer forest reproduction is usually annihilated by parasitic organisms.

After attempts to utilize peat substrata for farming or forestry failed, many of these lands were assigned as wildlife areas. The

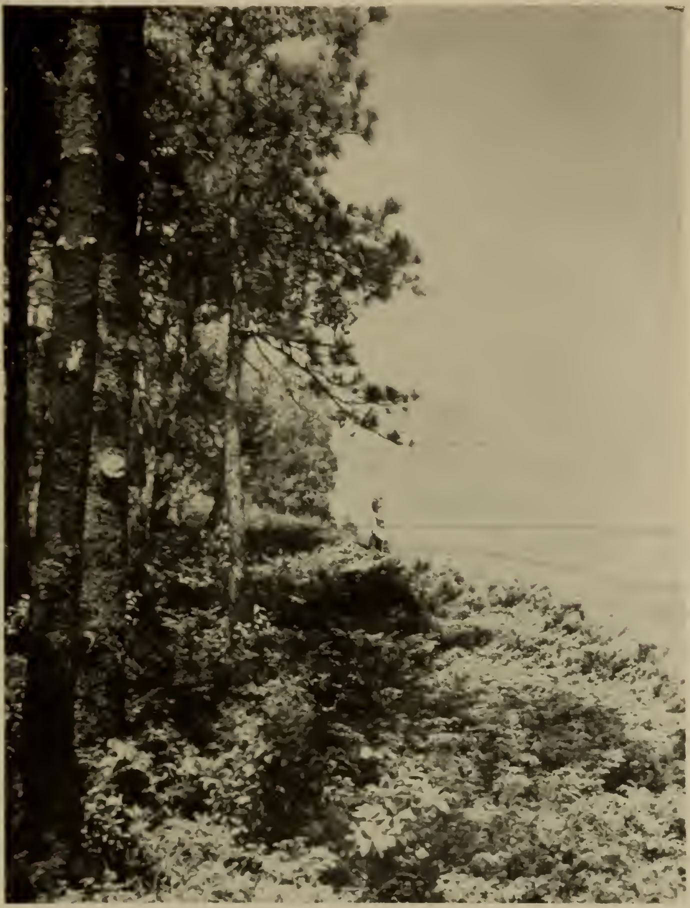


FIG. 6–3. Beech sand of Lake Michigan supporting white and red pines with a vigorous understory of creeping juniper. (Wisconsin Conservation Department.)

sad truth, however, is that "nothing will come of nothing," and soils deficient in nutrients cannot become productive, regardless of whether they are planted to rye, pine, or grouse. If these soils are to be returned to the productive class within reasonable time, their fertility must be raised by application of fertilizers and cultivation of legume crops.

Eroded soils. Under natural conditions, undisturbed by man's activity, the process of erosion or denudation is common to all soils of inclined topography, but it usually proceeds at a very slow rate and is seldom harmful to soil fertility. The loss of humus, mineral colloids, and soluble salts is, as a rule, compensated for by the decomposition of litter and the weathering of rocks. Harmful denudation, climaxing in the loss of the entire "top soil," usually follows clear cutting and plowing or grazing of lands, strip mining, and other soil-disturbing activities. The net result is a humus-deficient "subsoil" or "substratum" which is capable of producing only small yields of crops, farm or forest (Fig. 6–4).

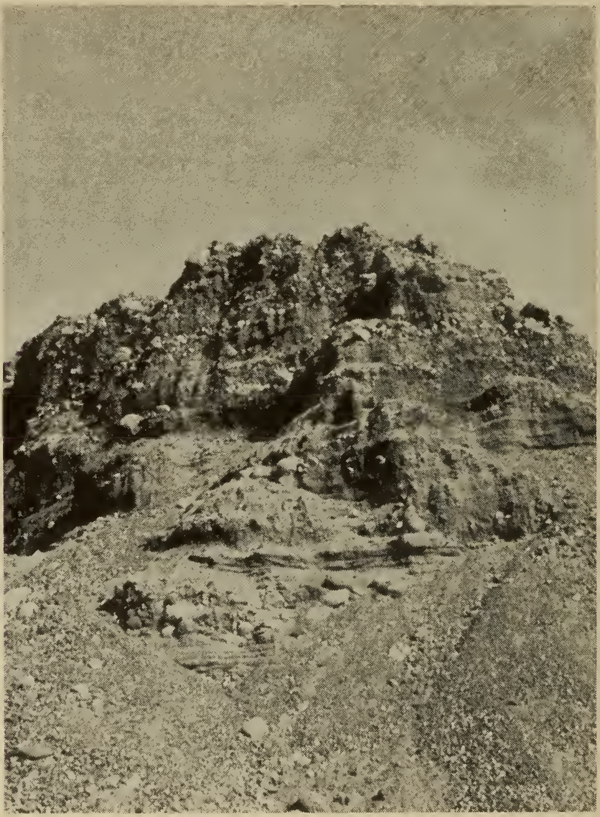


Fig. 6–4. Man-scalped earth awaiting plastic surgery to be performed by a forest specialist.

The properties of eroded soils vary within wide limits, depending upon the severity of erosion and the nature of exposed soil material. From the standpoint of silviculture, denuded calcareous strata present the most difficult problem, because only a few tree species can tolerate alkalinity and obtain sufficient iron from humus-deficient soils high in carbonates. Humus-free siliceous soils are just slightly better than depleted calcareous soils. Such soils have traces of nutrients and can be brought back into a productive state only by the use of the least exacting pioneer species. Comparatively better conditions for tree growth are found on eroded soils of granitic or ferromagnesian parent material.

Overwash soils. The depletion of land caused by erosion is in part balanced by deposition of the eroded material on level areas or slopes of moderate gradient. The soils formed on these deposits are usually enriched in organic matter and soluble salts; their moisture supply is augmented by runoff and often by seepage. Occasionally, the depth of the humus horizon in overwash soils reaches nearly 2 feet, and in the prairie-forest regions such soils are often confused with blackearths. In places, the overwash covers "relic" or buried soils, and thus soils of this type may have two or more humus horizons alternating with mineral strata.

Overwash soils are often marked by the occurrence of exacting tree species of exceptionally high rate of growth; a luxuriant understory of trees and shrubs is a characteristic feature (Fig. 6–5).

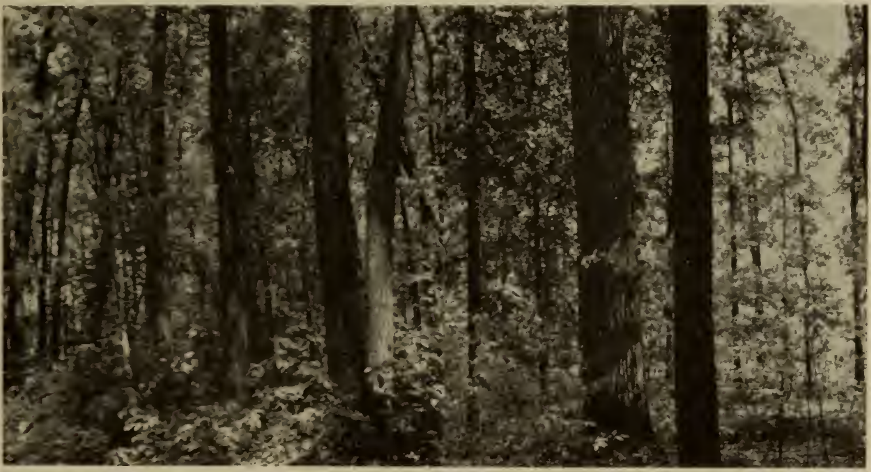


Fig. 6–5. A rapidly growing mixed stand of oaks, hickories, black walnut, and other hardwoods supported by an overwash silt loam enriched in humus, nutrients, and water brought down from surrounding slopes.

Stream-bottom and flood-plain soils. During periodic overflows these alluvial soils are enriched in humus, mineral colloids, and soluble salts. In places with a slow current the particles of humus and silt are sedimented as a sapropel-like homogenous mixture, called "muck." In bottoms of considerable gradient, alluvial deposits are usually well assorted by the fast currents and consist predominantly of coarse sand. Under the influence of inundation some soils of this group present an extreme example of soil dynamics, their morphology changing not only from place to place but from year to year.

Forest cover of alluvial soils is composed of water-loving species, some of which have considerable nutrient requirements. The stands are accompanied by numerous shrubs and a rich association of sedges, grasses, and nitrate-preferring herbs (Fig. 6–6). Stands of bald cypress, tupelo gum, and other hardwoods of the Mississippi lowlands are the world's outstanding examples of forests on alluvial soils. The rate of tree growth is largely correlated with drainage features and degree of oxygenation of ground water.

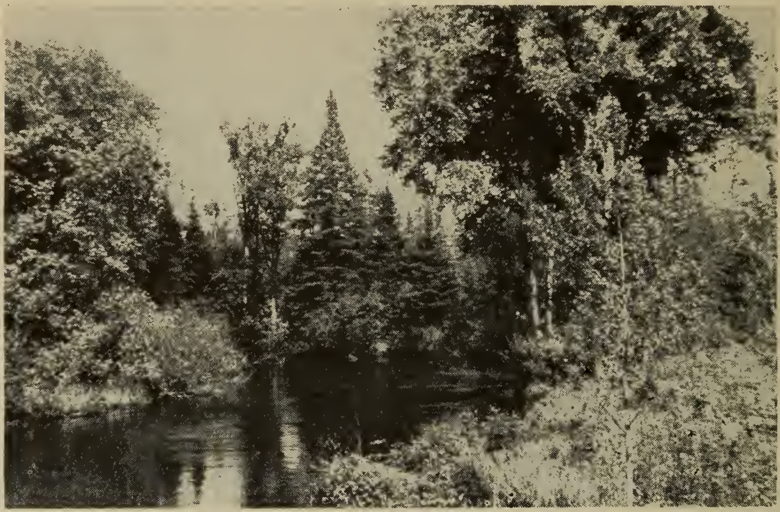


Fig. 6–6. Forest cover of an alluvial soil, a type which provides some marketable timber and pulpwood, as well as many benefits that cannot be evaluated in terms of dollars and cents.

Alluvial soils serve as natural highways for waterfowl and provide habitat for fur-bearers. While many alluvial soils offer limited possibilities of profitable forest exploitation, the preservation of forest cover on stream bottoms and flood plains is of great importance for the conservation of water, game, and fish.

MATURE OR GENETICALLY DEVELOPED UPLAND FOREST SOILS

Depending on physiographic conditions, genetically mature soils develop on **sialitic substrata** enriched in clay minerals, **calcareous substrata** of a high carbonate content, or on **litholitic, quartzitic,** and

feralitic substrata characterized by paucity of colloids possessing exchange properties.

On the basis of profile morphology mature forest soils of the world may be integrated into three broad genetic groups: **cryptorganic soils, melanized soils,** and **podzolized soils.** Morphology of representative profiles of these soils is illustrated in Figure 6–7.

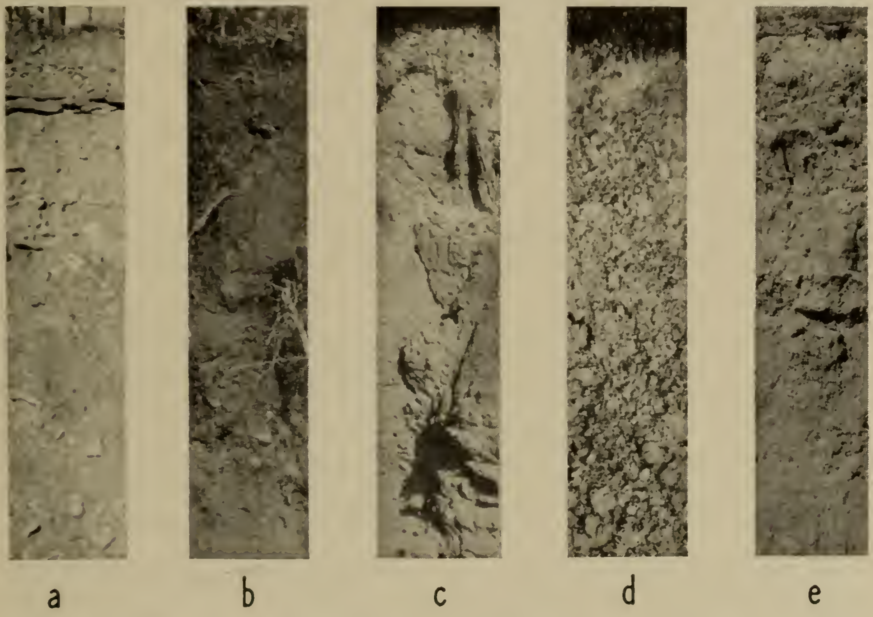


FIG. 6–7. Major morphological patterns of genetically developed or mature upland forest soils: (*a*) cryptorganic loam of sialitic substratum; (*b*) melanized sialitic loam of brownearth type developed on a granitic moraine; (*c*) hardpan podzol of a siliceous sandy outwash; (*d*) leached, nut-structured prairie-forest or grood silt loam of a calcareous drift; (*e*) podzolized or vadose clay of feralitic substratum.

CRYPTORGANIC SOILS

The development of these soils takes place under the influence of leucinization, a rapid and nearly complete decomposition of organic remains accompanied by the destruction of the black pigment of carbon compounds. Microbiological processes of this intensity proceed only in warm tropical environments and in a rather narrow marginal zone of the temperate region.

The profile of cryptorganic soils is composed of sporadic litter, a barely noticeable transitional zone with amorphous humus, and mineral soil of either light-gray, yellowish-tan, or red color. Cryptorganic soils occupy an immense total area in the tropical forest, the temperate rain forest, and a certain portion of the mesophytic deciduous forest. Although cryptorganic soils may occur on a variety of substrata, the most important groups of these soils are cryptorganic sialites and cryptorganic feralites or redearths.

Cryptorganic sialites. From the standpoint of intensive silviculture, primary attention should be given to cryptorganic sialites of the temperate zone: these soils support deciduous forests of exceptionally rapid growth and high commercial value. The largest continuous area of these soils is found in southern Indiana, Ohio, and portions of adjoining states. These soils lack pronounced genetic horizons and on superficial observation resemble embryonic soils; in fact, they have been classified as "soils with imperfectly developed profiles" (Marbut, 1935). The morphology of cryptorganic sialites is illustrated by the following description of a profile developed in southern Indiana under a virgin stand of tulip poplar, white oak, and beech (Wilde, 1951):

FH 0–¾ inches: Sporadic layer of last year's litter underlain by gray silt loam with occasional faint stains, dark-gray worm castings, and roots of ground cover plants; pH 6.7.

X_1 ¾–27 inches: Light grayish-brown silt loam of massive structure; color becomes yellow with depth; pH 4.7.

X_2 27–36 inches: Gray silty-clay loam with yellowish- and reddish-brown mottling; slightly pronounced columnar structure; pH 4.6.

As previous studies have shown (Weaver *et al.*, 1948), the strong acidity of these soils is not paralleled by enrichment of the surface layer in silica and accumulation of sesquioxides in the *B* horizon. Consequently, the soil remains in a state of constant equilibrium, a condition that must be expected at the frontier between podzolization and laterization. Table 6–1 presents the results of analyses of the described profile.

TABLE 6–1

PROFILE ANALYSES OF A CRYPTORGANIC SIALITE SUPPORTING A WHITE OAK-TULIP POPLAR-BEECH STAND IN DEARBORN COUNTY, INDIANA

Depth (in.)	Total N (%)	Available P (ppm.)	Exchangeable K	Exchangeable Ca	Exchangeable Mg	Exchangeable H
			(m.e. per 100 g.)			
0–3/4	0.262	28	0.37	21.92	2.60	1.08
3–6	0.065	16	0.19	0.22	0.47	6.55
9–15	0.055	12	0.19	0.22	0.48	7.63
24–36	0.039	20	0.28	0.39	1.51	11.82

In spite of an apparent deficiency of organic matter, a strong acidity, and a very low content of bases, cryptorganic sialites often support stands of exacting hardwoods yielding as much as 40 Mbf per acre, the world's record for deciduous forests of the temperate zone. The high productive capacity of cryptorganic soils must be attributed to the efficiency of their biological mechanism and a very short cycle of rotating fertility. The beneficial effect of rapid mineralization of organic remains was originally stressed by Süchting (1929), who maintained that the best type of humus is one that is never formed. The observations of forest growth on cryptorganic soils suggest that the true spirit of the soil is not necessarily the black carbon residue, or the "humus proper," but the ethereal end products of organic matter decomposition.

The forest cover of cryptorganic sialites on the North American and Eurasian continents is largely composed of species of tulip poplar, chestnut, oak, beech, maple, ash, walnut, hickory, and sycamore. The clear-cut logging or even heavy cuttings on these soils may drastically decrease their fertility. The destiny of soils lacking the horizon with resistant incorporated humus is illustrated by many deforested and now depleted soils of southern France and Italy. Even in the agriculturally young central part of the United States, cultivation has depleted many cryptorganic silt loams to the extent that they have become incapable of supporting hardwoods and have to be planted to nonexacting pine species.

Although climatic conditions in the tropical and equatorial regions are generally conducive to the development of feralitic parent materials, considerable areas are occupied by sialitic substrata (Harrassowitz, 1930). This is particularly true of localities covered with geologically youthful products of erosion and volcanic activity. Moreover, some forest stands in the humid part of the tropics are able to return feralitic soils to the class of sialites through the action of deep root systems and leaf fall affecting resilication and enrichment of surface soil layers in bases as well as clay minerals. The essential part of the process is a rapid mineralization of the enormous annual output of organic remains, approaching 100 tons per acre, and the infiltration of the products of decomposition to a depth of many feet. In spite of the fact that the infiltration of humates may raise the organic matter content to 10 per cent, soils do not exhibit a dark color (Vageler, 1933).

The predominant association on cryptorganic sialites of the tropics, the rain forest, is composed of several stories of trees and shrubs, numerous epiphytes and lianas. Nearly impenetrable stands of this type produce an enormous total volume of wood per unit area, but they have a low silvicultural or utilitarian value. The number of merchantable trees, such as mahogany, often does not exceed one or two per acre. Logging encounters great difficulties because of the density of stands and because of high percentage of worthless material.

The experiences of European colonists in Africa showed most convincingly the danger involved in clearing large areas of tropical rain forest. The removal of timber and the tractor cultivation of cryptorganic soils in a few years left behind substrata deprived of nutrients, partly because the lion's share of the nutrient capital of these soils is incorporated in the foliage of living trees (D'Hoore, 1949). Even under undisturbed conditions tropical sialites lacking incorporated humus often show a decline in their productive capacity, largely because their structure and permeability depend on the content of bases. With depletion of bases these soils become greasy like soap, attain a yellowish color, and finally undergo podzolization.

Cryptorganic feralites. The establishment of the tropical forests often takes place upon already feralized substrata impoverished to varying degrees in bases and silica (Mohr and Van Baren, 1954). Depending on the now existing climatic conditions, the silica-sesquioxide ratio of the parent material, and the type of established forest cover, the process of feralization may undergo essential alterations: it may proceed at the same rate (savannah forest); it may be arrested; or it may be replaced by the diametrically opposed process of sialization (rain forest). In the first instance the soil-forming process will culminate in an indurated redearth, or "true laterite"; in the latter case, the climax is a deferalized or sialitic soil of a cryptorganic or podzolic profile. It is obvious that the time factor of Dokuchaev plays a particularly vital part in the genesis of tropical soils, and, consequently, no strict correlation of soil profile morphology and vegetation can always be expected. For this reason, cryptorganic soils or other soils of feralized substrata can be encountered in any of the forest formations of the tropics, even though such soils are prevalent in regions with prolonged periods of drought. By and large, such regions are now occupied by monsoon and savannah forests.

The morphology of cryptorganic feralites includes a thin, often-sporadic layer of litter, a transitional zone of gray or gray-brown color less than one inch thick, and a bright-red substratum; the latter feature is responsible for the designation of cryptorganic feralites as "redearths" or "red loams." As with most tropical soils, the morphology and productive capacity of cryptorganic feralites depend greatly upon their content of bases. During the rainy season some bases are removed from the surface soil by leaching. A fraction of these bases is returned by leaf fall; a certain amount of bases may also be brought into the solum from weathering parent material. As a result, the reaction of the soil remains circumneutral as long as there is a sufficient supply of base-containing minerals to balance the losses caused by leaching. Under such conditions the oxides of iron, aluminum, and phosphorus remain immobile, and soils retain their granular structure. When the content of bases falls to less than 50 per cent of the exchange capacity, the development of the profile takes a new course. The lowering of the reaction to pH 5.5 brings a certain amount of sesquioxides into solution. In the dry season these are brought to the surface by the upward movement of stored rain water and are irreversibly coagulated (Agafonoff, 1930). The iron compounds are converted by oxidation into limonite and the soil may be enriched in so-called "pseudosand," "iron pea ore," and "perdigon" (Bennett and Allison, 1928). Eventually, the surface of the redearth may become covered with a cindery crust, signaling the conversion of a productive soil into an indurated redearth or "true laterite." In the climax stages of this process, the soil is transformed into "iron armour" devoid of any plant life, into a rock "which cannot be changed into soil by any conceivable process" (Vageler, 1933). Figure 6–8 illustrates the mechanism of the formation of ferruginous crusts observed in Hawaii by Sherman (1950).

Cryptorganic feralites support a considerable portion of the deciduous monsoon forest, a type of considerable interest to silviculturists. Because of periodic droughts, the understory of the monsoon forest is scant and lianas are few in number. Therefore, the interior of stands is accessible, and silviculture can be practiced much more easily than in the tropical rain forest. The stands include valuable species, particularly teak. This is one tree of the tropics which is cultivated artificially. Eucalyptus, with its extremely rapid growth rate and huge dimensions, is another remarkable inhabitant of cryptorganic feralites.

In drier portions of the tropics, the process of feralization increases in intensity, and the monsoon forest is replaced by savannah, extensive areas of grass and scattered umbrella-shaped or round-topped trees. This formation resembles to some extent the "oak openings" of the prairie-forest transition. Gigantic baobab, blackwood, silk-cotton or "kapok" tree, coconut palms, acacias, cabbage

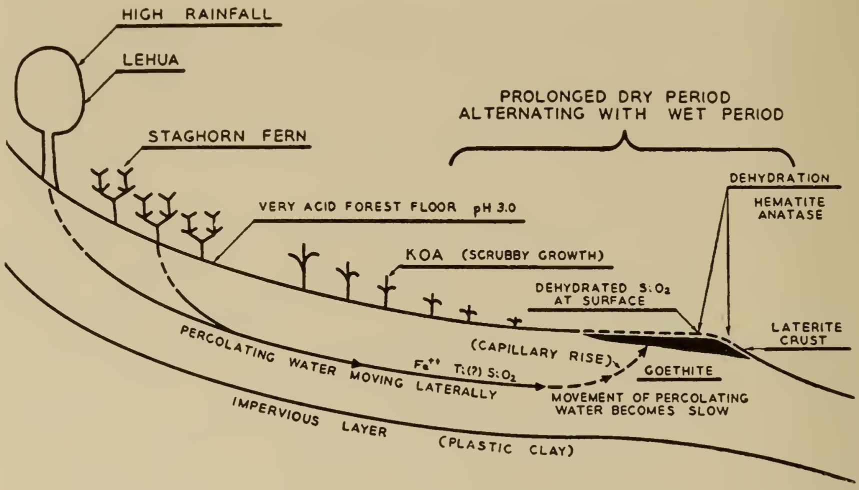

HIGH RAINFALL
LEHUA
STAGHORN FERN
PROLONGED DRY PERIOD ALTERNATING WITH WET PERIOD
DEHYDRATION
HEMATITE
ANATASE
VERY ACID FOREST FLOOR pH 3.0
KOA (SCRUBBY GROWTH)
DEHYDRATED SiO_2 AT SURFACE
LATERITE CRUST
(CAPILLARY RISE)
GOETHITE
Fe^{++} Ti(?) SiO_2
PERCOLATING WATER MOVING LATERALLY
MOVEMENT OF PERCOLATING WATER BECOMES SLOW
IMPERVIOUS LAYER
(PLASTIC CLAY)

FIG. 6–8. Development of the ferruginous lateritic crust under the influence of subterranean water. (After Sherman, 1950.)

tree, and arborescent euphorbias are the outstanding members of the savannah forest. Some of these trees occur on two or even three continents, thus forming a floristic link that connects the savannah forests of Africa, Asia, and America (Wulff, 1943).

In spite of periodic droughts some trees on moderately feralized redearths attain large dimensions, especially where savannah occurs at the edge of tropics or grades into a monsoon forest. However, large areas of the savannah forest have a low productive capacity because of severe feralization and occurrence of indurated redearths or true laterites. With decreased precipitation and on droughty

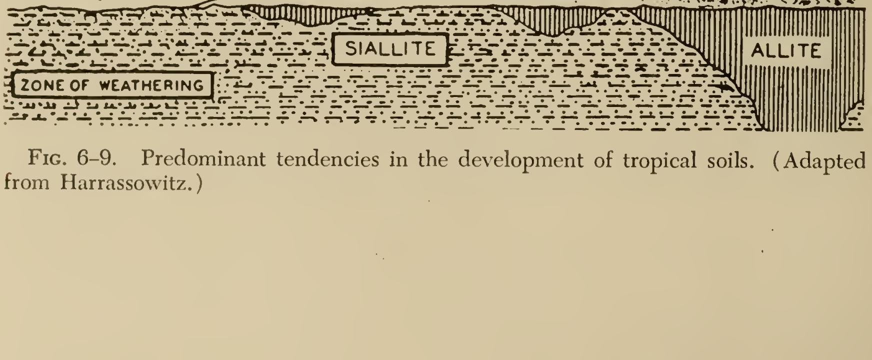


FIG. 6–9. Predominant tendencies in the development of tropical soils. (Adapted from Harrassowitz.)

sandy soils, the savannah gives way to the thorn forest of spiny acacias, euphorbias, and cacti; this is the most xeromorphic and picturesque but silviculturally useless formation.

The relative position of the major soil-forest units of the tropics is instructively presented by Harrassowitz (1930), whose scheme is reproduced in Figure 6–9. The genesis of feralitic crusts was recently elucidated by Aubert (1955).

MELANIZED SOILS

The surface humus-enriched layer of a dark or black color is not a property confined to chernozems and other grassland soils. A great portion of the world's forests is supported by soils whose profiles include dark, melanized layers varying in thickness from a few inches to over 2 feet. Both the activity of organisms and the buffering effects of this humus-enriched layer inhibit the development of other horizons, and melanized soils retain their *A–C* profile regardless of whether they are formed on sialitic, feralitic, skeletal, or any other parent material. In some instances, the composition of parent material overrules the effect of climatic factors and is directly responsible for the development of melanized soils in nearly all climatic provinces occupied by forest vegetation. Therefore, the pedogenetic classification of this soil group must of necessity be firmly anchored in the geologic or petrographic features of the substrata. A description of important varieties of melanized soils that possess distinct ecological characteristics and require essentially different silvicultural approaches follows.

Melanized sialites. By and large, these soils develop in the mild environment characteristic of the transitional zone between the climatic extremes of the boreal and the tropical regions. Adequate rainfall, moderate temperature, and short-lasting snow cover promotes a rapid decomposition of raw organic remains and an enrichment of the surface soil in amorphous humus (Fig. 6–10). These features, imparted by the balanced conditions of moisture and temperature, preserve the stability of silica and sesquioxides. The equilibrium of silica and sesquioxide compounds in these soils may also be regarded as the outcome of the frontogenetic clash of the two diametrically opposed soil-forming tendencies: impoverishment of the surface horizons in iron and aluminum oxides, common to podzol soils, and accumulation of the same compounds in the surface layers of feralitic soils.

It is obvious that the delicate equilibrium of these two trends in the transitional zone can easily be disrupted by the co-influence of

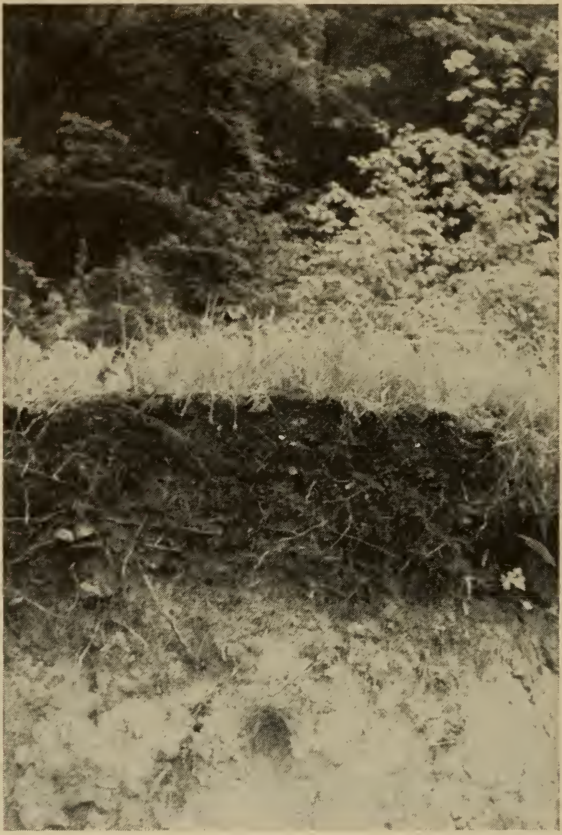


FIG. 6-10. A representative profile of a well-developed melanized soil of sialitic substratum supporting a mixed stand of hardwoods. Vicinity of Freiburg, southern Germany.

topographical features, parent rock, and vegetative cover (Mancini, 1955). As the result, melanized sialites occur as island-like fragments of a mosaic formed by podzolic soils, cryptorganic soils, and soils exhibiting signs of feralization.

The simple morphology of melanized sialitic soils is exemplified by the following description of a profile from the region of American central hardwoods:

A_0 Sparse remains of last year's litter.

A_1 0–16 inches: Dark-brown, nearly black, crumbly, fine sandy loam enriched in organic matter, penetrated by roots, and harboring earthworms; somewhat lighter in color and compacted in the lower part of the horizon; pH 6.7.

C 16–36 inches: Grayish-brown loam of granulated structure, with many roots and root channels; pH 7.2.

Table 6–2 presents results of analyses illustrating the distribution of important constituents in the profile of a melanized sialite.

TABLE 6–2

TOTAL ANALYSIS OF A MELANIZED SIALITIC LOAM SUPPORTING A STAND OF HARDWOODS (S. A. WILDE AND W. E. PATZER)

Depth (in.)	N	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	P_2O_5
				Per cent				
0–8	0.221	73.51	3.28	8.27	1.61	0.59	1.04	0.11
8–16	0.073	77.80	3.47	8.15	0.96	0.47	0.87	0.09
16–30	0.041	82.05	3.46	8.29	0.88	0.46	0.75	0.12
30–40	0.006	82.20	4.01	7.49	1.73	1.06	1.18	0.08

Although the reaction and the content of bases in melanized sialites are subject to wide fluctuation, these soils possess high exchange capacity and usually an adequate supply of available nutrients. They support rapidly growing and valuable stands composed predominantly of mesophytic hardwoods, such as maple, tulip poplar, beech, chestnut, walnut, hickory, ash, basswood, and oaks. A detailed account of forest cover on melanized soils of the United States was given by Braun (1950); its European equivalent was described by Mayr (1909). Forests on these soils are characterized by the abundant production of mast, consisting of chestnuts, acorns, beechnuts, walnuts, and nuts of hickory and other species; therefore, the expression "hardwood mast forest" may be applicable to this broad forest type.

Under the influence of environmental conditions melanized sialites acquire certain characteristics common to either podzolic or feralitic soils. In the warmer and drier portions of central and southern Europe, their profiles are enriched in iron and attain an intensive brown color, a property which gave rise to the designations "brownearth" (Ramann, 1918) and "brown forest soils" (Walter, 1951). For several reasons the concept of "brownearth" was and still is fettered by confusion (Wilde, 1946). In the colder and more humid environments melanized soils acquire gray-brownish or gray color and are classified by Russian pedologists (Glinka, 1931) as "diorn soils" (sward soils) or "weakly podzolized" and "cryptopodzolic soils." Such soils are frequently formed in the very heart of the podzol region by the influence of milder microclimatic conditions, parent material rich in bases, hard ground water, and forest cover of so-called "soil-conserving" species, such as maple, ash, basswood, beech, and hornbeam.

In tropical regions melanized soils of sialitic substrata occur on youthful parent materials enriched in bases and alumino-silicates, or under forest cover that counteracts the process of feralization. In the latter case the formation of secondary clay minerals is promoted by the pumping action of deep-rooted trees and mineralization of abundant leaf fall. Forest stands occupying soils of this group present the most compact and diversified association of the tropical rain forest; in some of the stands as many as eighty tree species may be found on a single acre. The unique structural pattern of these highly organized communities is largely responsible for the exorbitant adjectives used in descriptions of rain forest: "impenetrable," "mysterious," and "forbidding." The fear that such an environment generates is not instigated by the presence of tigers or other big cats but by winged inhabitants which distribute malaria, sleeping sickness, and yellow fever.

Within the climatic optimum of their development, as well as in the inhospitable boreal environment and in the humid tropics, the islands of melanized sialites always served as mainstays of agricultural endeavors. As testified by many writings, the first aim of homesteaders in forested regions was to find land with a dark layer of incorporated humus, be it called "terreau," "mold," or "black dirt."

During the past century several microthermic conifers, especially Norway spruce, were introduced on melanized soils in central European countries. However, neither climatic conditions nor the properties of the soil proved to be satisfactory for these species. The introduction of conifers often produced a rapid leaching of soils and their conversion into podzolized soils or even true podzols.

Rendzinas or melanized soils of calcareous substrata. The term **rendzina** is associated in the minds of Polish farmers with soils which emanate unpleasant screeching sounds as the blade of the plow scrapes the substratum or fragments of limestone.

Rendzinas are the most conspicuous representatives of melanized soils, distinguished by their nearly black and often deep horizons with incorporated humus. The humus-enriched layer rests on either fine-textured, skeletal, or consolidated calcareous substratum. On superficial observation these soils are often similar to chernozems, and their morphology well justifies their original designation as **humus-calcareous soils.**

Rendzinas occur sporadically throughout the regions of northern coniferous forests, prairie forest, mesophytic hardwoods, and occasionally are found even in the areas affected by laterization. They are formed on soft limestones, chalk, lime-bearing shales, and various lime-enriched deposits. Soils formed on parent materials of a high carbonate content are called **eurendzinas**, whereas soils developing on partly siliceous substrata are called **pararendzinas** (Kubiena, 1948).

In the earliest of his works Glinka (1908) considered rendzinas as "endodynamomorphic" soils, which are not influenced in their development by climatic factors. Additional investigations, however, revealed that soils of calcareous rocks are subject to the same alterations as soils of any other parent material and in time attain morphology of podzolic soils or soils of other climatic-zonal types. As the result, Glinka (1931) not only retracted his original nomenclature but even vigorously objected to its outmoded use (Wilde, 1948). Figure 6–11 illustrates successive stages in the evolution of a rendzina, as observed by Lebedev (1906).

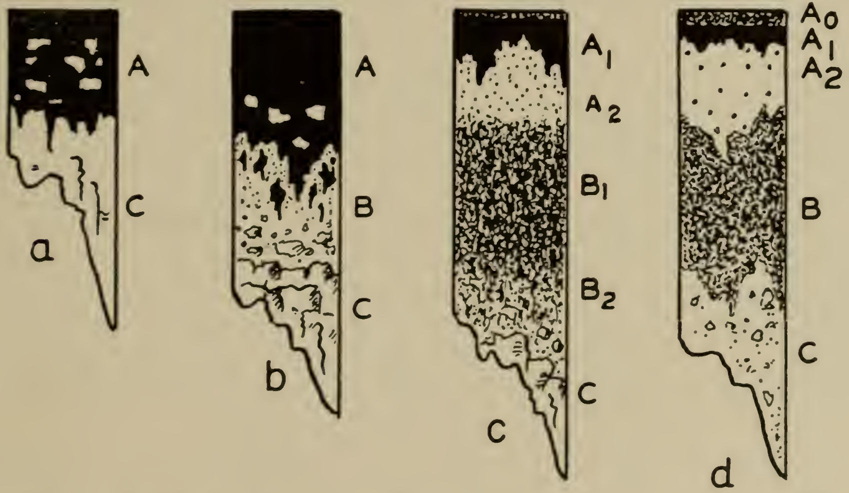


FIG. 6–11. Metamorphosis of a rendzina into a podzolic soil: (*a*) immature skeletal rendzina; (*b*) fully developed rendzina or prairie soil; (*c*) degraded rendzina or grood soil; (*d*) podzolized rendzina or podzolic soil with calcareous substratum. (After Lebedev, 1906.)

Depending on climatic conditions, content of carbonates, and texture of parent material, rendzinas exhibit several varieties. In highly humid and cold environments of boreal forest, outcrops of calcareous rocks become waterlogged and develop peatlike raw humus of nearly neutral or alkaline reaction. This layer is underlain by a black melanized zone whose thickness is determined by the depth of weathered material. In spite of their alkaline reaction these **raw humus** or **ectorganic rendzinas** support acidophilous trees, such as spruce and fir, in addition to lime-tolerant white cedar, juniper, balsam poplar, and other deciduous species. Another variety of the ectorganic rendzinas, found on varved calcareous clays, carries a thick layer of so-called "fine mull" humus, a black, sawdust-like detritus of arthopod castings and exoskeletons (Wilde *et al.*, 1954). These chernozem-like boreal rendzinas are among the choice lands of the northern forests.

In warmer and less humid environments forest litter on calcareous substrata undergoes rapid decomposition, and amorphous humus is incorporated with weathered material by soil organisms and infiltration. In many instances the process of melanization is sponsored by grasses whose partly decomposed root systems give rise to intrazonal **prairie soils** (Marbut, 1928).

Recently, rendzinas were carefully studied by Kubiena (1948), who recognized several environmental and successional phases in the development of these soils. **Protorendzinas** are shallow humus-calcareous soils found in high altitudes and on rocks in the initial stages of their weathering; these embryonic soils are usually droughty and unproductive. **Tangel rendzinas** are raw humus rendzinas developing in high mountains under the cover of heath plants, rhododendron, and juniper; their raw humus layer is enriched in earthworm castings—a phenomenon quite common in both melanized and podzolized calcareous soils of the boreal zone. **Mull rendzinas** are fine-textured calcareous soils with deep melanized layers formed by stable clay-humus complexes. **Brown rendzinas** represent the initial stage of metamorphosis of rendzinas into brown-earth, grood, or podzolic soils. **Terra fusca** is the term applied to "degraded" rendzinas of brown color, enriched in clay and exhibiting massive structure and inadequate permeability.

A unique example of a large area of rendzinas in the warm and humid region of laterized substrata is presented by the "lime prairies" of Mississippi. This wide belt of black clays or clay loams, developed from weathered cretaceous limestone, supports sporadic growth of post oak, jack oak, red cedar, honey locust, crab apple and plum (Hilgard, 1906).

Because of their enormous distribution, rendzinas support a highly diversified forest cover, including magnificent stands of spruce and fir in the podzol region and stands of struggling, dwarfed oaks in the prairie-forest transition.

Embryonic groods or melanized prairie-forest soils. When chernozem or prairie soils are invaded by forest, the canopy of trees moderates evaporation, retards the melting of the snow, and thus increases the amount of water which percolates through the soil profile. Forest litter provides chemical and biological agents which increase the solubility of both organic and mineral compounds. As a result, the humus is gradually removed from the upper soil layer, which attains a lighter color. As farmers of the prairie regions say, "the forest devours the blackearth." The released silica appears in the profile as white dust or "frosting," and the sesquioxides accumulate in the lower part of the soil profile, thus converting the blackearth into a leached prairie-forest soil or grood soil. This process of "degradation" of grassland soils by forest cover, however, proceeds at a slow rate, especially when the invading forest does not include species of pronounced podzol-forming traits. Under the cover of jack pine or hard maple, prairie soils of the American Midwest preserve for centuries their original profile. Therefore, a considerable portion of forest stands in the prairie-forest transition is supported by melanized soils that are designated as **embryonic groods.** A profile description of a representative soil of this type, supporting a 180-year-old stand of hard maple and associated hardwoods, follows (Pierce, 1951):

A_0 Sporadic cover of maple leaves.

A_1 0–15 inches: Zone of humus incorporation. Dark, nearly black silt loam of crumbly structure with diffused lower limits, heavily penetrated with roots and inhabited by earthworms, white grubs, ants, and myriapods.

A_1A_2 16–19 inches: Transitional zone. Silt loam of similar structure and appearance except of lighter brownish color.

A_2B 19–35 inches: Humus-impoverished zone. Light-brown silty clay loam of coarse blocky structure, penetrated by passages of large roots and practically free of earthworms and insects.

C 35–48 inches: Structureless yellowish-brown silty clay loam, underlain at a greater depth by weathered limestone.

Depending on geographic location, forest cover on embryonic groods consists of a variety of tree species, including pines, aspen, balsam poplar, oaks, and other hardwoods. The growth and reproduction of trees on embryonic groods are handicapped by competition of prairie vegetation, erratic distribution of mycorrhizal fungi, and often by alkaline reaction and high concentration of salts. Many of these properties are gradually ameliorated by progressive leaching of soils and their gradual conversion into podzol-like leached grood soils.

A conspicuous type of forest cover on embryonic groods is the so-called "oak openings," a savannah-like landscape of grassland with scattered oaks. This battleground of trees and grass played a vital part in the history and colonization of the American Midwest. James Fenimore Cooper and other American writers have given vivid descriptions of life in this peculiar environment which once abounded in buffalo, deer, sharptailed grouse, and other fur- and feather-clad inhabitants.

Melanized soils of coarse siliceous substrata. As a general rule, the occurrence of melanized soils outside of their climatic optimum is determined by the abundance of bases and the presence of hard ground water or forest cover of soil-conserving hardwoods. A notable exception to this rule is the development of melanized soils promoted by extremely unfavorable conditions. The low water-retaining capacity and the paucity of nutrients in siliceous sandy soils permit the existence of only partly open forest stands of pioneer pines and scrub oaks. Such stands are invaded by xerophytic grasses and less-exacting legumes, whose decaying roots produce a melanized surface layer. A description of a typical profile follows:

F A thin layer of pine needles and oak leaves.

A_1 0–6 inches: Rhizogenous sandy mull of nearly black, humus-enriched sand, penetrated by the roots of grasses; pH 5.9.

C 6–52 inches: Light-brown sand grading into coarse, yellow, loose sand underlain by Cambrian sandstone; pH 6.7 to 7.0.

Besides the profile morphology melanized sands are distinguished by the entire absence of ground-cover plants common to podzolized soils, such as *Maianthemum, Mitchella, Linnaea,* and *Pteridium.*

Occasionally, cultivation of podzolic sandy soils destroys their leached horizon and produces a dark, sharply delineated layer, about 8 inches thick. The true nature of such artificially created, pseudo-melanized soils, however, is usually revealed by the presence of a compacted, brown *B* horizon underlying the plowsole.

Subarctic melanized soils. In the proximity of tundra, forest stands on elevated plateaus are supported by melanized soils which originally were classified as "boreal mull soils" (Tkachenko, 1911), "latent podzols" or "incipient podzols" (Glinka, 1931), and "dark primitive soils" (Filatov, 1945). Recently these soils were described under the name of "subarctic brown forest soils" (Kellogg and Nygard, 1951).

Examination of soils along the south-north transect, laid out across the podzol region, clearly shows that the process of podzolization decreases in its intensity toward the arctic circle and becomes completely arrested in the tundra zone. Therefore, the development of stable melanized soils in the tundra-forest transition should largely be attributed to climatic conditions which preclude the translocation of sesquioxides in soils not influenced by runoff or ground water.

The rather unusual morphology of subarctic melanized soils is characterized by a layer of matted root mor a few inches thick, a brown crumbly mull layer, often enriched in earthworm castings, and a light-brown to yellowish-brown substratum, which at a greater depth exhibits mottling and may grade into permafrost. These soils, together with some of the boreal rendzinas, belong to the group of melanized soils covered with raw humus. In sharp contrast to the acid peat bogs and swamp podzols of the surrounding depressions, melanized soils of boreal uplands at times possess slightly acid or even neutral reaction. Detailed analyses of several representative profiles were reported by Kellogg and Nygard.

The forest includes slowly growing microthermic species, such as spruce, larch, birch, aspen, and alder. The ground cover consists predominantly of raw humus plants and invaders from tundra soils, although occasionally highbush cranberry, spring beauty, wild rose, and other inhabitants of the mull humus soils are present. Subarctic melanized soils occupy a large total area in the tundra-forest transition of Eurasia, Alaska, and Canada but provide only a small fraction of the world's forest products. They may play an important part in the future if and when the population pressure forces agricultural endeavors to the subarctic wilderness.

Alpine sward soils. The development of these melanized soils of skeletal substrata, or "mountain sod soils," takes place under the influence of alpine meadow vegetation, which invade open forest stands near the timber line. The roots of grasses enrich the coarse regolith in humus and consolidate it into a compacted layer of sod or "sward." Depending upon environmental conditions and the age of the soil, the dark brown or gray surface layer varies in depth from a few inches to nearly 1 foot; it rests on substratum that contains as much as 40 per cent gravel. Thus, the profiles of alpine swards resemble blackearths of the plains and at times were referred to as "mountain chernozems." This analogy finds additional support in the adaptation and the productive capacity of these two soils. Like chernozems, the alpine swards produce low yields of poor timber but are valuable grazing grounds. Alpine swards, with their high content of nitrogen, are in part responsible for the fame of the Swiss dairy industry.

The origin of parent rock exerts a strong influence upon the morphological characteristics of alpine swards, their productive capacity, and alterations imposed by age. The **siliceous sward**, or "Ranker," in Kubiena's terminology (1953), is a petrographic variety which readily undergoes podzolization. The **calcareous sward,** or "skeletal rendzina," on the other hand, has a tendency to maintain the vegetation of alpine grasses and metamorphizes into podzolic soil only through a long evolutionary catena. However, the sporadic forest cover and greatly restricted silvicultural possibilities of mountain sward soils do not justify a detailed description of their numerous transitional forms.

Efforts are now being made in several European countries to elevate or restore the timber line by reforestation of alpine meadows and by reinforcement of forest stands on sward soils. This difficult task is largely undertaken for the protection of the lowlands from avalanches and catastrophic floods. In this connection alpine sward soils may be subjected to a much more detailed study than has been done in the past. Such investigations, however, will have to deal with the depth, texture, internal drainage, availability of nutrients, and other properties in addition to the genetic characteristics of soils to be afforested.

Melanized feralites. These soils are distributed in the regions of tropical and subtropical rain forests and monsoon forests; they are largely confined to elevated plateaus and base-enriched parent materials permitting the maintenance of a reaction above pH 6.0. Under such conditions soils develop a dark-brown melanized horizon which at times extends to a depth of several feet. Soils of this morphology often exhibit excellent crumb structure, and according to Vageler (1933), they are "the dream of the agricultural pioneer." Some melanized forest soils of the tropics are related to **margalitic** or **regur** soils formed on calcareous substrata (Mohr and Van Baren, 1954).

A description of melanized feralites, or "reddish-brown lateritic soils," is included in the Yearbook of Agriculture (U.S.D.A., 1938); the total analyses of the "mulatto" and related soils, given by Bennett and Allison (1928), are of particular interest in regard to the profile composition of tropical soils enriched in humus. A description of a "red latosol" profile, answering the morphology of a melanized feralite, was reported by Kellogg and Davol (1949). This profile is located in the region of the rain forest in Belgian Congo; its features are briefly outlined:

> 0–1 inch: A thin layer of brown organic remains covering dark, reddish-brown clay; porous and friable to firm granular. Organic matter content approximately 12 per cent; pH 6.1.
>
> 1–8 inches: Reddish-brown structured clay, firm but friable, with many roots and insect holes. Organic matter about 4.5 per cent; pH 6.1.

8–13 inches: Transitional layer.

13–19 inches: Yellowish-red clay of subangular medium nut structure. Organic matter 1.2 per cent; pH 5.9.

72 inches plus: Light-red to reddish-yellow clay with quartz pebbles and stones; zone of intensive weathering.

Although melanized feralites support mahogany, teak, ebony, sandalwood, logwood, and other valuable tropical hardwoods, their silvicultural possibilities are greatly restricted by the competition of agricultural crops, as well as oil, rubber, drugs, and fruits. Melanized feralites are the principal soils of the tropics that preserve a reasonable degree of fertility after clear cutting and cultivation. Nevertheless, indiscriminate use may ruin even these so-called "inexhaustibly rich tropical soils." With the exception of cotton and a few other annuals, most tropical crops are mycorrhizal woody plants whose successful artificial culture is dependent on the supply of humus.

PODZOLIZED SOILS

Podzol is a Russian term derived from the old Slavonic words *poda* (soil) and *zola* (ash); it pertains to the color of the siliceous leached layer which at times has the appearance of "soil ashes." The essence of podzolization is the removal of iron and aluminum sesquioxides from the surface horizon and concentration of these compounds in the lower part of the soil profile. Therefore, the terms "sesquioxide-leached soils" and "endoferalic soils" express the nature of podzolized soils equally well. In the outmoded but entirely justifiable terminology of the old-time foresters, podzols were known as "raw humus soils" (Sigmond, 1924). Raw humus, with all its complex biological and chemical influences, is the chief factor directly responsible for the cardinal characteristic of podzolization process, the translocation of difficultly soluble oxides of iron and aluminum (Müller, 1878; Emeis, 1908).

Originally, the mechanism of podzolization was explained on the basis of the effect of free hydrogen ions, released in decomposition of organic remains. The disclosure of the wide occurrence of strongly podzolized soils of neutral and alkaline reaction considerably broadened the purely chemical concept of podzolization. According to recent beliefs podzolization proceeds largely under the influence of microorganisms and by-products of their metabolism. As a result of absorption of mineral salts by organisms, action of reducing agents, and formation of complex humates, the bases as well as iron and aluminum sesquioxides are brought into solution or colloidal suspension and are leached from the surface layer. At a certain depth the mobile fractions are precipitated or flocculated because they reach the isoelectric point, become dehydrated, or for other reasons as yet unknown; some enrichment of the lower horizon may also result from the mineralization of the microbial tissues transported by percolating water.

Podzolization is a very specific process, proceeding under the influence of retarded decomposition of forest litter, but this term is now often used as if it were synonymous with either leaching or surface gleization—phenomena common to a great variety of soils. This unqualified use of the term confuses climatic zonal classification of soils on every continent (Wilde, 1953).

Podzols. This designation usually refers to the climax in the development of sesquioxide-leached soils, as illustrated by the following description of a profile under a hemlock stand in northern Wisconsin:

A_0 4 inches. Layer of raw humus, or mor, consisting of strongly acid (pH 4.0), matted, dark-brown organic remains penetrated by fungus mycelia and giving off a peculiar "sour" odor. Line of demarcation between organic matter and mineral soil is sharply defined.

A_1 Not present.

A_2 4–16 inches. Light-gray, nearly white sand with irregular tonguelike lower limits; pH 3.8.

B_1 16–27 inches. Slightly cemented sandy loam of a reddish-brown color with some concretions (Ortsand); pH 4.0.

B_2 27–45 inches. Firmly cemented rocklike hardpan layer of a dark, coffee-brown color (Ortstein), free of tree roots; pH 4.0.

C Stratified sand.

Table 6–3 gives the results of a profile analysis of a hardpan podzol.

TABLE 6–3

PROFILE ANALYSIS OF A HARDPAN PODZOL SUPPORTING HEMLOCK, YELLOW BIRCH, AND BALSAM FIR. TERMINAL MORAINE IN LANGLADE COUNTY, WISCONSIN (S. A. WILDE AND S. F. BURAN)

Horizon and depth (in.)	N	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	P_2O_5
				Per cent				
A_2: 4–12	0.02	79.03	1.31	9.77	0.44	0.48	1.71	0.01
B: 24–36	0.06	69.02	4.10	18.05	1.79	0.74	2.40	0.64
C: 44–52	Tr.	75.47	2.98	11.12	1.73	0.64	2.43	0.20

The hardpan layers of mature podzols sometimes attain a thickness as great as 4 feet (Fig. 6–12). Depending upon the proportions of iron and humus in the *B* horizon, podzols are classified into "iron podzols" and "humus podzols" (Ramann, 1911; Frosterus, 1914). The development of the latter type is correlated with impeded drainage and a particularly thick layer of raw humus (Tamm, 1920). In fine-textured soils podzolization develops sticky and mottled claypan layers similar to gley horizons formed by ground water. The soils of this nature do not differ greatly in their ecological effects from poorly drained soils and are sometimes classified as "gley podzols." In this way podzolization may produce poorly drained soils on uplands far above the real water table. Both hardpan and claypan layers of podzols inhibit the growth of root systems and render forest stands vulnerable to windfall.

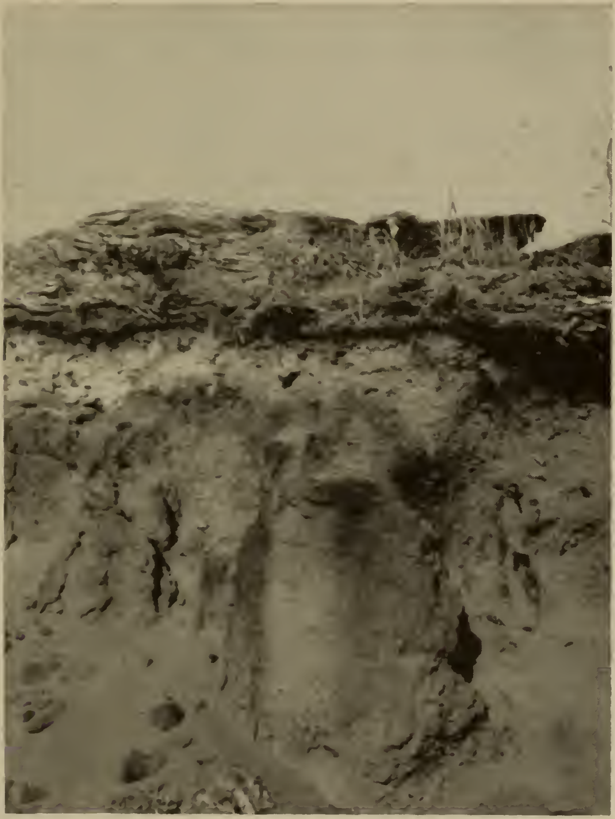


Fig. 6–12. A profile of an ortstein podzol with a 4-foot-thick stonelike hardpan. Note the size of the white pine log, which has survived since the eighteen-nineties.

The largest share of podzol soils supports the "taiga" forest, composed chiefly of conifers: spruce, fir, hemlock, pine, and larch. The occurrence of deciduous trees is largely limited to aspen, birch, alder, mountain ash, and willows.

On the basis of homonyms, in the Russian language the word "podzol" sounds evil. And from the viewpoint of a farmer, it is indeed an evil soil regardless of its topography, texture, or degree of stoniness. The supply of nutrients in podzol soils is concentrated largely in the raw humus layer, which upon clearing, undergoes rapid decomposition and leaves quartzose residue impoverished in nitrogen and other nutrients. In order to bring an acre of a depleted podzol soil to a productive state, it is necessary to apply 5 or more tons of lime and 1000 pounds of a complete fertilizer; the cost of these materials alone would nearly buy an acre of fertile soil. An entirely different picture, however, is viewed by a silviculturist. Under natural conditions podzol soils support coniferous stands that show moderate rates of growth, but in time still produce high yields of valuable timber. Only after clear cutting, the adverse effects of podzols become pronounced. In reforestation of cut-over lands the growth of planted trees on podzols may be hindered by lack of nutrients in the leached layer, impermeability of the accumulative layer, and unfavorable effects of the accumulative layer on the distribution of moisture during wet and dry seasons.

Podzolic soils. Rather unfortunately, there is only a slight dissimilarity between the words "podzol" and "podzolic," which hardly expresses the enormous difference in the adaptation and productive capacity of these two types. Podzolization in a mild form is, silviculturally speaking, one of the most beneficial processes; it immensely increases the productivity of forest soils, especially those of sandy texture. In the course of podzolization the soil accumulates a substantial layer of superficial organic remains which serve as a storehouse of buffered nutrients. Moreover, mineral colloids and humate suspensions, redeposited at a depth of about 1 to 2 feet, materially increase the water holding capacity of the soil. While nonpodzolic sandy soils usually produce a dozen cords of jack pine at the age of forty years, podzolic sands yield at the same age as many as 20 cords per acre.

As a transitional type, the profile of podzolic soils exhibits the characteristics of both melanized soils and podzols. The ectorganic layer of a fairly friable structure in these soils seldom exceeds 2 inches in thickness. It rests on a thin layer with incorporated humus. The podzolic horizon is underlain by a reddish-brown accumulative layer, compacted but permeable to roots; at times the *B* horizon contains concretions, iron lacework of "pseudomycelium," or permeable "ortsand." The reaction of the soil usually varies between pH 5.0 and 6.0. The following profile description illustrates the morphology of a moderately podzolized morainic loam:

> *F* 0–2 inches: Leaves of maple and needles of hemlock and fir grading into a loosely consolidated layer of duff; an acid but biologically active layer; pH 5.5.
>
> A_1 2–5 inches: Dark-gray loam rich in humus; pH 5.7.
>
> A_2 5–14 inches: Light-gray, siliceous, fine sandy loam with occasional dark patches of humus; pH 5.2.
>
> *B* 14–32 inches: Reddish-brown, stony loam, slightly compacted but penetrated by tree roots; pH 5.5.
>
> *C* 32 inches plus: Compressed till.

Podzolic soils dominate the entire southern border of the podzol region; their distribution coincides closely with the occurrence of the broad zone of mixed hardwood-coniferous stands. The forest cover of this silviculturally important zone includes species of spruce, fir, hemlock, pine, maple, beach, basswood, yellow birch, elm, and oak. Podzolic soils usually have a very high capacity for natural regeneration. The pioneer stands are largely composed of pine, birch, and aspen.

Crypto-podzols. Examples of soils with concealed podzolic horizons are encountered in the podzol region on cut-over or burned-over areas that remained under grass cover for several decades. The decomposition of grass roots on such areas imparts a dark color to the profile, thereby masking the leached layer of the soil. At the same time the infiltration of humates does not appreciably modify the cementation or compaction of the *B* horizon. Therefore, the podzolic nature of such soils can be revealed by ocular examination and verified by the determination of iron and aluminum oxides in different layers.

Analyses of soils from many old cut-over areas showed that the masking effect of grass cover has little influence on the fertility of crypto-podzolic soils; such soils preserve their strongly acid reaction, and their surface layers remain impoverished in nitrogen and other nutrients.

In many instances the designations "crypto-podzols," "latent podzols," and "weakly podzolized soils" are applied to melanized soils occurring within the podzol region—that is, soils which show no translocation of sesquioxides. Such misuse of terminology is usually influenced by climatic-zonal ideas of soil classification, according to which all upland soils within a particular climatic region must eventually attain the zonal morphological pattern. The fallacy of such assumptions is clearly demonstrated by studies of prairie and other nonpodzolic soils supporting artificially established coniferous plantations. Under conditions favoring podzolization the translocation of sesquioxides and subsequent discoloration of the upper layer of the soil take place within the brief period of forty years (Müller, 1887; Tkachenko, 1908; Wilde *et al.*, 1949). Therefore, a forested soil which failed to undergo podzolization in the course of many centuries is in stable equilibrium with its environment, and its classification as a podzolic soil has neither scientific nor silvicultural justification.

Occasionally, artificial planting of coniferous species on melanized soils produces a transitional type of **incipient podzols**, morphologically closely related to crypto-podzols. Such soils develop a layer of true raw humus, 2 to 3 inches thick, which rests directly on dark mineral soil with incorporated humus (Ohmasa, 1952).

Leached grood soils or degraded chernozems. The invasion of the prairie by the forest in time superimposes the process of podzolization on the profile of either chernozems or prairie soils. The resulting transitional varieties, however, possess certain features distinguishing them from podzols, and they comprise a separate group of prairie-forest or **grood soils.**

"Grood" is a folk term that has been adopted by forest pedologists (Kruedener, 1927; Morozov, 1930) as a substitute for earlier synonyms: "nut-structured soils," "gray forest soils," and "degraded soils" (Korzhinsky, 1891; Sibirtzev, 1901). This term refers to the structural aggregates characterizing the profile of prairie-forest soils; as well as to the type of forest cover which these soils support—a type distinctly different from the associations of podzolic soils (Pogrebniak, 1931; Wilde, 1940). Kruedener (1927) makes the following statement in his *Waldtypen*: "Rural people in their efforts to enlarge the agricultural area, very well appraised the differences in productivity of the grood and podzol types." In American literature grood soils were described under the names of "gray-brown podzolic soils" (Baldwin, 1928; Marbut, 1935; Kellogg, 1936), "gray forest soils" (Joffe, 1936), and "degraded chernozems" (U.S.D.A., 1938).

Under the influence of forest litter, a part of the incorporated humus is removed from the surface layer of the blackearth and together with the bases and sesquioxides is translocated into the lower region of the soil profile (Fig. 6–13). In calcareous soils of the prairie-forest transition, the percolation of water usually

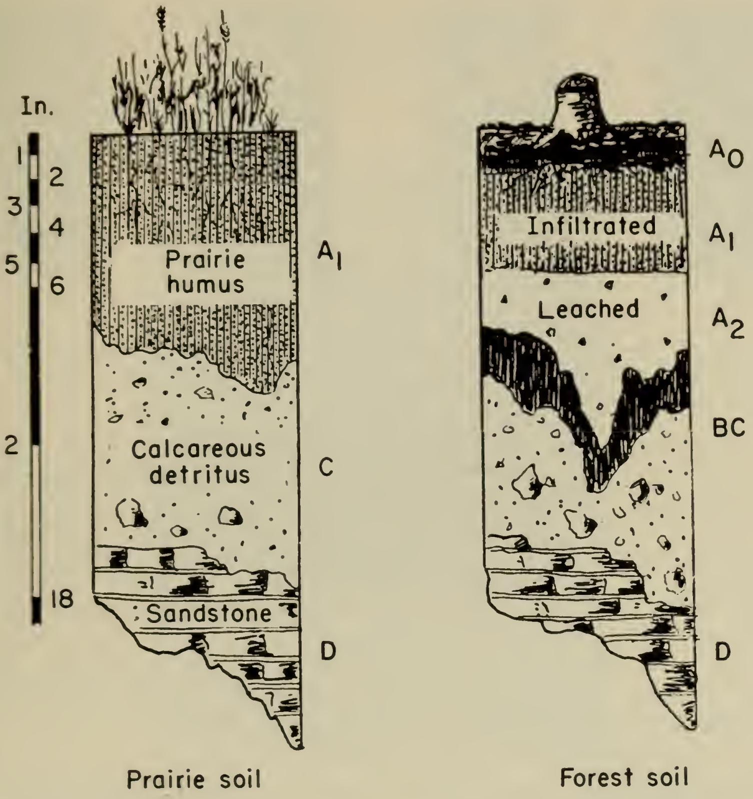


FIG. 6-13. Morphological features of a shallow prairie soil formed on a calcareous detritus under the cover of grasses, and a leached forest soil of similar geologic origin developed under a stand of oak species. The profiles are only 200 feet distant from each other. Sauk County, Wisconsin. (After Elisabeth Chanvannes, 1940.)

is not sufficiently deep to remove carbonates from the substratum (Wissotzky, 1930). However, the root systems of trees extract carbonates of calcium and magnesium and thus create a network of voids which leads to the development of the peculiar prismatic, "nutlike" structure, especially pronounced in the *B* horizon (Fig. 6-14). The following description outlines the morphological features of a leached grood profile, developed under an oak-hickory stand:

A_0 0–2 inches. Undecomposed oak leaves, acorns, twigs, and other organic remains.

A_1 2–8 inches. Dark-gray silt loam high in organic matter, mellow and smooth to the touch, breaking into fine aggregates. It contains a considerable number of small earthworms and is penetrated by a network of roots; pH 6.5.

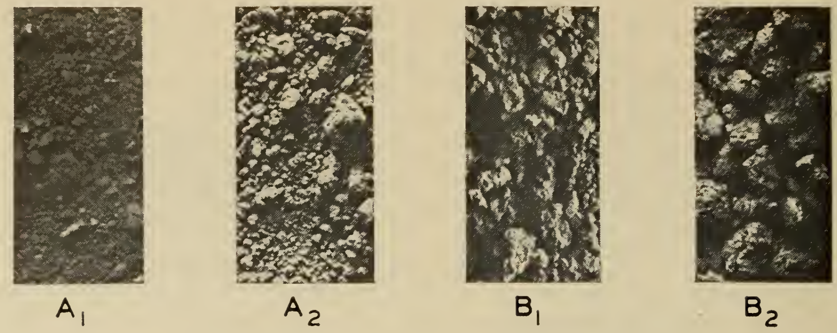


Fig. 6–14. Structural characteristics of the various horizons of a nut-structured grood silt loam soil, the type predominant in the prairie-forest transitions of North America and Eurasia.

A_2 8–16 inches. Light-gray to tan, brittle silt loam of a distinct platy structure. Plates are "frosted" with siliceous dust; pH 5.6.

B_1 16–34 inches. Chocolate-brown silty clay loam breaking into larger aggregates about the size of a small hazelnut and exhibiting grayish siliceous powder when dry. Nuts are honeycombed by a number of very fine channels. Penetrated by tree roots and with some large earthworms in root channels; pH 5.8.

B_2 34–48 inches. Reddish-brown clay loam with rusty streaks. Contains some carbonates and has a tendency to break into large clods in the upper portions of the horizon; pH 7.8.

C 48 inches plus. Carcareous detritus.

The results of analyses of this profile are given in Table 6–4.

TABLE 6–4

Total Analysis of a Nut-structured Grood Loam Formed Under a Stand of Oak and Hickory in Southern Wisconsin (S. A. Wilde and D. P. White)

Horizon and depth (in.)	N	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO
			Per cent			
A_1: 0– 4	0.300	73.03	2.23	8.34	0.981	0.624
A_2: 4–12	0.040	78.74	2.47	8.94	0.692	0.127
B_1: 16–24	0.030	71.40	4.37	10.12	0.930	0.632
B_2: 36–48	0.015	64.98	4.71	11.90	1.472	0.953
C: 56–60	0.003	76.12	2.17	8.28	1.850	1.245

Leached grood soils show a remarkable morphological and chemical uniformity throughout the enormous expanse of the prairie-forest transition of North America, Europe, and Asia (Levchenko, 1930; Tiurin, 1930; Wilde, 1940). In part this uniformity stems from the fact that most of these soils are developed from loess, parent material of the same origin and composition. The prairie descent of grood soils is often marked by "krotovinas," earth-filled burrows of prairie rodents (Fig. 6–15).

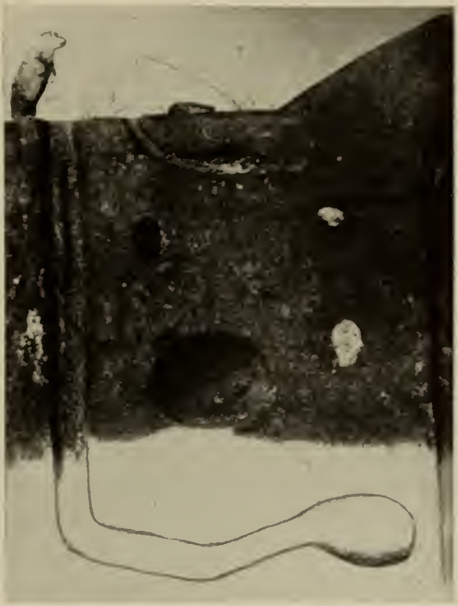


Fig. 6-15. Rodent burrows, the so-called "krotovinas," harboring prairie dog, gopher, and mouse—a feature common in soils of prairie-forest transitions. (L. Althausen.)

In time the leaching may remove most bases from the *B* horizon, destroy structural aggregates, and thus convert a leached grood soil into a podzolic soil. In some instances grood soils are invaded by prairie grasses and undergo melanization or "regradation," a process resulting in the transformation of groods into chernozems or prairie soils.

The predominant forest cover of grood soils consists of oak and hickory species with some ash, black walnut, elm, hornbeam, boxelder, and catalpa. In advanced stages of succession these stands are partly replaced by maple and basswood. In the colder part of the steppes, leached groods or "degraded chernozems" support aspen and conifers.

Leached groods present the greatest contrast in revenues obtained from agricultural and silvicultural land utilization. These soils, with their abundant supply of nutrients and nearly ideal physical makeup, are among the world's best for the production of farm crops. At the same time, grood soils support forest stands of mediocre growth rate and poor quality. Because forest growth improves with advanced leaching, the terms "degraded chernozem" and "degraded prairie soil" are contrary to the forester's viewpoint.

In places, grood soils are dissected by strips and islands of alkali soils: **solonchak** or saline soils, **solonetz** or nonsaline alkali soils (also called "black alkali soils"), and **solodi** or leached alkali soils (U.S. Salinity Laboratory, 1954). With minor exceptions alkali soils are highly unfavorable to tree growth, their toxicity increasing with the content of exchangeable sodium and concentration of soluble salts. The sporadic forest cover of these soils includes struggling oaks and a few halophytic trees, such as Kirghizean birch and saksaul. Fairly productive stands, however, may be encountered on strongly leached solodi soils of acid reaction. By and large, forest trees find their way to alkali soils as constituents of shelterbelt and farm woodlot plantings aimed at soil conservation and amelioration of climatic conditions.

Calcareous podzols or gray wooded soils. The development of these soils is confined largely to lime-bearing glacial and lacustrine deposits in the colder parts of the northern coniferous forest.

Because of the high content of carbonates in the parent soil material and the enrichment of tree foliage in bases, forest litter acquires a nearly neutral or alkaline reaction. Under such conditions podzolization of the soil is effected largely by hydrolysis and activity of microorganisms releasing water soluble metabolic by-products. The roots of trees, penetrating calcareous substrata, in time remove a considerable portion of calcium and magnesium carbonates. This produces a decrease in the volume of the soil and contributes to the development of a prismatic structure. In soils subjected to strong percolation of water, mineral and organic compounds undergo translocation into the lower part of the soil profile and form compacted or indurated horizons enriched in carbonates as well as sesquioxides.

The morphology of podzolized calcareous soils is exemplified by the following description of a profile from the Algoma region, northern Ontario (Wilde, Voigt, and Pierce, 1954):

A_0 0–2.5 inches: Matted mor penetrated by fungus mycelia and roots of ground vegetation. Nearly neutral.

A_1 2.5–4 inches: Dark-gray, faintly structured loam, high in organic matter and of nearly neutral reaction. In places the horizon is not discernible.

A_2 4–11 inches: Light-gray loam of platy structure exhibiting pronounced signs of podzolization and with a diffused lower boundary. Moderately acid.

B 11–30 inches: Light brown, silty clay loam of prismatic structure exhibiting slight grayish mottling; penetrated by coarse roots of trees. Slightly acid to neutral.

C 30–54 inches: Light-brown silt loam with pronounced yellowish mottling. Alkaline and high in carbonates.

Soils of this morphology were first classified as calcareous podzols by Tkachenko (1911), who observed them on lime-bearing substrata in northern Russia. Later these soils were located on large areas of Canada and designated as "gray wooded soils," a not-too-fortunate designation. This term is a translation of the Russian *serye lesnye pochvy* (gray forest soils), a name originally applied to strongly degraded chernozems of the prairie-forest transition, that is, soils formed in an essentially different climatic environment than calcareous podzols. The expression "wooded soils" is not in the spirit of contemporary technical English and especially discordant to the ear of a forester.

Although calcareous podzols are ecologically very distant from the grood soils of the prairie-forest transition, these two soil groups have a certain morphological similarity of profiles. By a freakish coincidence the expression "gray wooded" abbreviates into "grooded" or simply "grood" soils. It is not excluded, therefore, that the term "boreal groods" may be suitable for the designation of leached calcareous soils formed in the podzol zone of Canada, northern Europe, and Siberia.

Forest stands of calcareous podzols include species of pine, spruce, fir, and larch with incidental admixture of aspen, balsam poplar, and birch. The ground cover consists entirely of "raw humus" plants. Thus, the composition of forest vegetation of calcareous podzols is essentially similar to that of podzols found on noncalcareous substrata. In spite of this, calcareous podzols are distinguished by an exceptionally high rate of forest growth. According to Tkachenko (1911), mixed coniferous stands on calcareous podzols produce 250 per cent higher yields than on noncalcareous podzols.

There is evidence that calcareous podzols present a successional or "degraded" phase of boreal rendzinas. In advanced stages of podzolization, surface layers of calcareous podzols acquire a strongly acid reaction as low as pH 4.0, although their lower layers preserve an alkaline reaction of pH 8.0. Large areas of such **podzols of calcareous substrata** are found in the northern part of the Great Lakes region.

Mountain podzols. The profiles of these soils are composed of a raw humus layer, a leached horizon, and an accumulative horizon enriched in iron and aluminum oxides. The latter often merges with the parent rock. Because of the low content of mineral colloids and infiltration of dark-colored humates, mountain podzols frequently have less distinct profile features than podzols of the plains. Nevertheless, their analysis reveals a pronounced depletion of bases and sesquioxides in the upper layer. Accumulative horizons exhibiting cementation or iron concretions are found only occasionally. The content of organic matter in the surface 6-inch layer frequently exceeds 10 per cent.

The mountain podzols support microthermic species, such as spruce, alpine fir, larch, mountain pines, birch, willows, and mountain ash. The stands of these species grow at a slow rate because of the short growing season, but in advanced age they may produce high yields of extremely valuable fine-grained timber, some of which is used for high-priced pianos and stringed instruments.

On steep slopes, as well as in areas subject to periodic overflow, the podzolization may be entirely concealed, and the soils attain morphology or crypto-podzols resembling those of the tundra zone.

Red and yellow podzolic soils. These terms are applied to leached soils of feralitic substrata which are largely confined to the regions of subtropical and temperate rain forests (U.S.D.A., 1938). Such soils have only a thin layer of free organic remains and occasionally have a weakly developed horizon with incorporated humus. The leached layer consists of a yellowish-gray or grayish-brown quartzose residue and is underlain by intensely colored yellow or deep-red feralitic material grading into a mottled clay substratum. The analyses of upland soils show that the colloids are not concentrated in a distinct accumulative horizon but increase progressively to a depth of several feet (Marbut, 1935). It is possible that the flocculation of the colloidal suspensions is hindered by the hydrogen saturated exchange material and the paucity of electrolytes in the entire soil profile.

The morphology of a red podzolized soil is illustrated by the following description of a profile developed under a stand of longleaf pine in southern Mississippi:

A_0 A layer of loose pine needles.

A_1 1 inch: Dark layer of sandy loam with some incorporated humus.

A_2 1–9 inches: Reddish-gray, leached, sandy loam; strongly acid.

BC 9–30 inches: Intensely red to reddish-brown clay of faint, coarse lump structure, somewhat compacted and sticky, with dark-brown veins and flakes; acid.

C 30 inches plus: Sticky and mottled clay of massive structure.

There is only limited knowledge concerning the genesis of red and yellow podzolic soils. In the opinion of some pedologists such soils of the southeastern United States, France, the Caucasian region, and Japan were formed on fossil laterites which survived from the tropical environment of the Tertiary Period (Stebutt, 1930). According to recent ideas the discoloration of the surface layers in podzolized lateritic soils is effected largely by vadose water, that is, surface gleization rather than podzolization (Bogatyrev, 1954). The color of yellow soils has been attributed to their youth, incipient podzolization, or previously impeded drainage (Stremme, 1915; Marbut, 1935). The difference in color, however, does not seem to be of any ecological importance.

Both red and yellow podzolic soils are strongly acid and have a low content of nutrients. Regardless of their texture, these soils are often only suitable for pines and other less exacting trees. In the United States they are occupied by shortleaf pine, longleaf pine, loblolly pine, slash pine, and oak species. Because of the moderate nutrient requirements, pines attain a rapid growth and produce comparatively high yields on short rotations. An abundant supply of moisture, a very long growing season, accessibility of stands throughout the year, and favorable conditions for both natural and artificial reforestation are among the silviculturally important features of red and yellow podzolic soils. These soils now provide a substantial share of forest products of the United States.

Tropical podzols. The process of podzolization in tropical regions is effected by several conditions: heavy precipitation, abundant leaf fall, and impoverishment of substrata in electrolytes. The latter is common to all mature soils influenced by the process of feralization. The extremely acid raw humus and the development of true podzols is especially common in regions where annual rainfall approaches 300 inches (Lang, 1915) or on siliceous parent materials invaded by heathlike ericaceous plants (Richards, 1952).

The podzolization of soils becomes pronounced as soon as their reaction falls below pH 5.5; it follows essentially the same course as podzolization in the temperate zone. The feralitic parent material, or its upper portion, may lose some iron and aluminum oxides and acquire a rather wide silica-sesquioxide ratio (Harrassowitz, 1930). Consequently podzols of the tropics may be of either sialitic or feralitic substrata.

Hardon (1937) gives the following description of a podzol profile from Indonesia which is nearly identical with podzols of the cold climates, except for the extreme acidity of the humus layer.

A_0 0–2½ inches: Half-decomposed, black, organic material mixed with coarse sand; pH 2.7.

A_1 2½–10 inches: Loose, grayish-black, humic, coarse sand; pH 3.9.

A_2 10–16 inches: Loose, grayish-white coarse sand.

B_1 16–28 inches: Hardpan. Dark brown, very compact coarse sand; pH 3.9.

B_2 28–40 inches: Loose, light-brown coarse sand; pH 4.6.

The podzol soils of either sialitic or feralitic substrata are confined largely to the tropical rain forest but occasionally may be encountered in the monsoon forest. The value of tropical podzol soils as a medium for plant production decreases in direct proportion with the increase in leaching and acidity. Soils with a deep-leached horizon are particularly poor in nutrients and undesirable for agricultural use. Hardpan layers present a serious obstacle to the cultivation of deep-rooted plants, especially rubber. Podzols and related raw humus soils of the tropics have been until recently entirely overlooked by investigators; in fact, statements may be found in the older literature denying the possibility of any appreciable accumulation of organic remains in tropical or subtropical soils. Actually, the thickness of raw humus layers in some tropical forests approaches 1 foot.

Charral or littoritic soils. The term "charral" is used by Latin Americans as a synonym for parklike sclerophyl forest, a distinctive floristic formation which is confined to the littoral districts of the subtropics (Schimper, 1898; Dengler, 1930). The most important areas of the sclerophyl or "leatherleaf" woodlands are on the European and African coasts of the Mediterranean Sea, and near the seashores of southern Africa, central Chile, California, and southern Australia. These regions are characterized by sharp contrasts in climatic conditions: mild rainy winters and hot summers with prolonged periods of drought.

The dry summers impart a pronounced xeromorphic stamp on the floristic cover and lateritic features to the red or reddish-brown soils. Nevertheless, the total annual precipitation approaches the high level of 30 inches. The resulting large quantity of water percolating through the soil profile during the cool season is responsible for the translocation of colloidal substances and the development of the enriched *B* horizon, a process resembling podzolization. Such enrichment, however, may be the result of purely physical illuviation of clay, independent of the biochemical translocation of sesquioxides (Principi, 1953). This assumption may be valid, because all littoritic soils exhibit a rather rapid decomposition of raw organic remains.

The illuviation of mineral colloids and soluble salts contributes to a coarse prismatic structure of the enriched layer which in mature soils attains a more intense color. The differentiation of horizons is especially pronounced in soils derived from noncalcareous parent materials. Some of the soluble salts, translocated in winter, are returned to the surface stratum by the activity of plants and summer evaporation. Therefore, the entire body of the soil tends to retain its supply of bases and its circumneutral reaction. Acid soils occur on purely siliceous substrata.

Genetically, charral soils may be considered as relatives of savannah soils in which feralization is less pronounced and is partly offset by podzol-forming tendencies. The soils supporting sclerophyl forest in California were originally related by Thorp (1936) to the brown soils of Shantung province of China. Later they were designated by an ambiguous term "non-calcic brown soils" (Baldwin *et al.*, 1938). These soils usually have an abundant supply of calcium and support predominantly calciphilous trees, including both deciduous and coniferous species. In the opinion of Gračanin (1948), some of

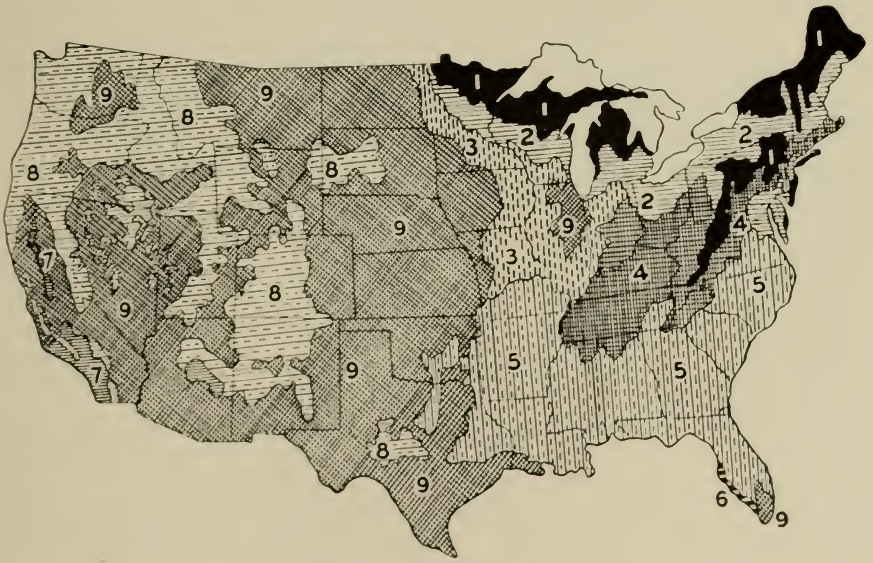


Fig. 6–16. Forest and soil provinces of the United States: (1) northern conifers—predominance of podzols; (2) mixed hardwood-coniferous forests—podzolic and melanized soils; (3) prairie forest—nut-structured grood soils, rendzinas; (4) central hardwoods—melanized, cryptorganic, and vadose soils of sialitic substrata; (5) southern pine and hardwood forests—podzolized, vadose, and melanized soils of feralitic substrata; (6) subtropical forest—mangrove swamps; (7) sclerophyl forest—charral or littoritic soils; (8) western coniferous forests—semidesert soils, melanized and podzolized mountain soils, alpine sward soils; (9) grasslands and deserts.

the littoritic soils, particularly terra rossa, are iron-enriched parent materials exposed by erosion. When such substrata are invaded by vegetation, their organic matter content increases and, in Gračanin's terminology, they undergo a process of "brownization." This initial stage of soil formation from partly feralized calcareous parent material may be followed by leaching and the development of a podzol-like soil.

As a broad group littoritic soils embrace several petrographic varieties, such as "terra rossa" of hard limestone substrata, the iron-rich "ferretto," siliceous "macchie" soils of southern Europe, the "fynbush" soils of South Africa, and the ferruginous sands of Australia. However, all these varieties have a subordinate silvicultural importance. The sclerophyl forest of evergreen oaks, laurels, olives, and other hard-leaved trees and shrubs, occasionally accompanied by megathermic pines, junipers, and cypresses, exhibits within its entire range the same general floristic appearance and low rate of tree growth.

While the leatherleaf forest has little value as a source of timber, some of the charral soils provide incomparably greater returns under planned management than do other groups of forest soils. Charral soils are well adapted to the production of citrus trees and many other valuable horticultural plants of sclerophyllous nature. From the broader viewpoint of tree culture, therefore, these soils deserve much greater attention than they have received in the past.

Figure 6–16 outlines the major soil-forest provinces of the United States.

The growth factor which must be accorded the first place is water.
—E. Warming, 1895

7

Hydromorphic forest soils

As the designation implies, hydromorphic soils develop under the influence of water which occurs in a quantity sufficient to suppress oxidation processes and activity of aerobic microorganisms. An excessive content of water usually results from either a true or a perched ground water table. In some localities, a low permeability of the surface layer causes "puddling" or accumulation of superficial vadose water which imparts to the surface soil characteristics of a gley horizon. In highly humid boreal and mountain regions, surface soil layers are enriched in water of condensation or nonmeasurable precipitation. Depending upon the source of water and degree of soil saturation, the following major groups of hydromorphic soils are recognized: **gley soils**, **vadose** or **pseudo-podzolic soils**, and **organic soils** of either **highmoor** or **lowmoor** type.

GLEY SOILS

Anaerobiosis and hydrolysis, dominating the strata of the soil below the water table, produce deoxidized, often highly dispersed, sticky gley horizons, mottled with reduced oxides of iron and other elements (Wissotzky, 1905). Soils in which the gley layer occurs within the reach of the root system of trees or cultivated plants, that is, at a depth of approximately seven feet or less, are classified as gley soils.

The process of gleization may affect any genetic group of soils. The resulting varieties are referred to as gley podzols, swamp podzols, gley laterites, vlei soils, meadow soils, lowland prairie soils, ferruginous soils of mountain valleys, and marl soils. Ordinarily, gley soils occur sporadically, being confined to depressions and areas underlain by impervious substrata. However, in certain regions of America, northern Europe, Siberia, and Africa, gley soils are a dominating type occupying hundreds of thousands of acres.

In detailed genetic classifications the variations in the degree of soil drainage, or in the intensity of gleization, are expressed by a number of terms, such as gley podzol, swamp podzol, podzolic gley soil, podzolic gley soil with a deep gley layer, peat podzol, gley podzolic peat soil, peaty gley soil, and swamp gley soil (Zavalishin and

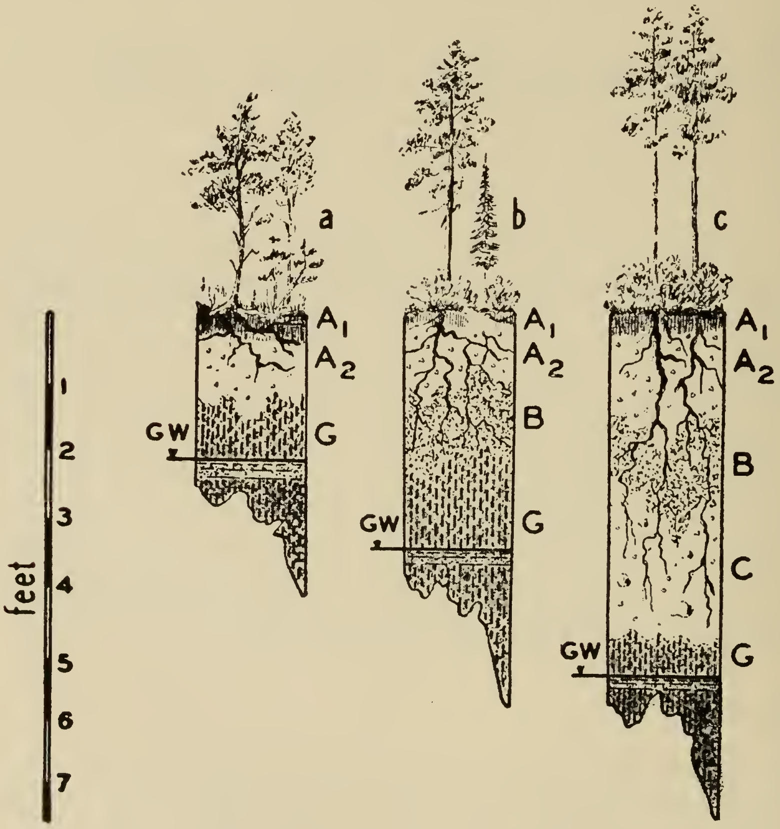


Fig. 7–1. Position of the waterlogged zone (*G*) in different types of gley soils: (*a*) shallow-gley soil; (*b*) mid-gley soil; (*c*) deep-gley soil. The position of the gley horizon and subsequent depth of the well-aerated soil determine in a large measure the extent of root penetration, the supply of water, air, and nutrients, and the stability of the stand against wind.

Pronevich, 1928). These and similar terms have significance in basic studies of soil genesis, but they are too long and confusing for practical soil classifications. Moreover, they have no direct bearing upon the productive capacity of forest soils.

The composition of the forest stand, its rate of growth, its percentage of cull, the vigor of competing vegetation, possibilities of natural reproduction, stability of the forest against the wind, and other silviculturally important features are chiefly influenced by the distance of the gley layer from the surface; this distance to a large degree determines the proximity of the free water, the extent of root penetration, and the depth of well-aerated soil containing nutrients (Wilde, 1940). Considering the depth and position of the gley layer in relation to the occurrence of the *A*, *B*, and *C* horizons of a mature forest soil profile, the following three types of gley soils may be recognized (Fig. 7–1):

Alpha-gley soils or shallow gley soils: Semiswamp, more or less permanently wet soils with a gley layer grading into the *A* horizon.

Beta-gley soils or mid-gley soils: Insufficiently drained, periodically wet soils with the gley layer superimposed upon the *B* horizon.

Gamma-gley soils or deep gley soils: Sufficiently drained and aerated soils with a gley layer occurring in the *C* horizon (Fig. 7–2).

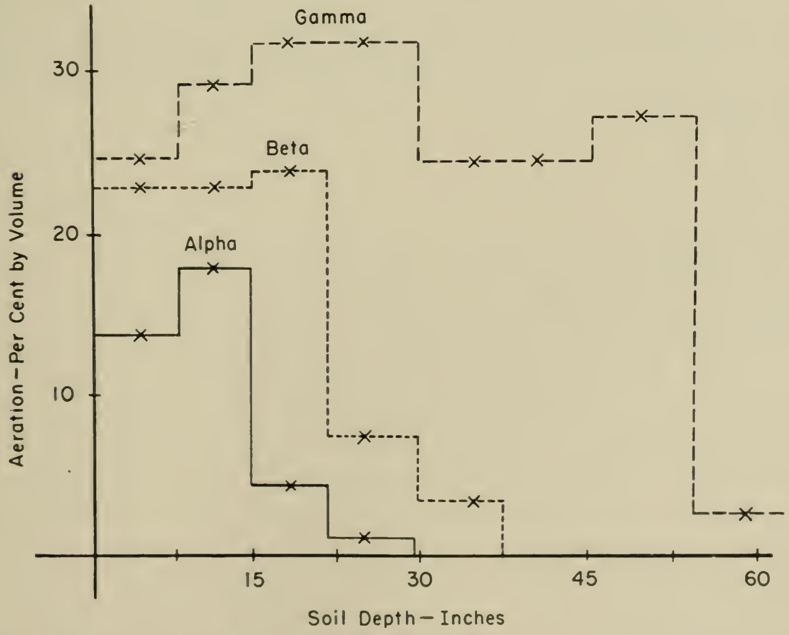


FIG. 7–2. Aeration of gley soils underlain by ground water at an approximate depth of 25 (Alpha), 40 (Beta), and 70 (Gamma) inches.

Alpha-gley soils (shallow gley soils). The gley layer extends through the leached horizon and may reach the horizon with incorporated humus, being thus within about one foot of the surface. In this type the influence of the ground water often masks all the other genetical features of the soil profile. Soils of semiswamp flats of lacustrine clays or highly colloidal weathered deposits of early glaciations, various swamp-border soils, and some stream bottom soils are conspicuous members of this group.

The forest cover of alpha-gley soils is composed of a rather limited number of species which can tolerate deficiency of aeration. Spruce, balsam fir, cedars, tamarack, bald cypress, pitch pine, black ash, elm, river birch, swamp white oak, cottonwood, and tupelo gum may be cited as typical representatives. With some exceptions, the stands are of a low productivity and have a high percentage of cull (Zavalishin, 1928; Büsgen and Münch, 1929; Tamm, 1950).

Beta-gley soils (mid-gley soils). The gley horizon occurs immediately below the accumulative layer and sometimes grades into the latter, thus being at a depth of two to three feet below the surface. Percolating water and ground water contribute equally to the morphology of these soils. The soils of lower slopes in the mountains, shallow outwash or residual soils underlain by impervious strata of weathered shale or boulder clay, some red and yellow lateritic soils underlain by hardpan, and podzols of heavy texture with highly colloidal accumulative layers are typical examples of beta-gley soils.

In the summer, the surface layers of these soils are usually dry. In the fall, and particularly in the spring, however, water saturates the entire surface layer. An excavation of open trenches, or boring with an auger, is necessary to reveal the presence of the typical mottling of the gley horizon and the nature of these soils.

Being a transition, this type of soil offers a suitable site for the survival of both upland and lowland forest trees, even if it does not assure their good growth. Consequently, the forest cover is often composed of numerous species, both conifers and hardwoods. The rate of growth and the stability of forest stands on beta-gley soil are decreased by a number of adverse conditions. The roots of the trees are confined to a comparatively shallow surface layer of well-aerated soil. As a result, the supply of available nutrients is limited. Periodic saturation and the effect of early and late frosts greatly shorten the length of growing season. Upland species suffer in spring and fall from inadequate soil aeration, whereas lowland species suffer and sometimes perish in summer from drought. The abundance of weakened specimens encourages the development of parasitic organisms which contribute to the general decadence of forest stands. These soils are most unfavorable to deep-rooted deciduous species; in drought-free regions they occasionally support heavy stands of spruce and other tolerant conifers.

Gamma-gley soils (deep gley soils). The gley horizon reaches its full development in the lower part of the parent material, usually at a depth of from five to seven feet. However, slight mottling may occur at a depth of about four feet. The development of mull humus is often characteristic of gamma-gley soils. In all other respects, the composition of the soil profile is but slightly influenced by the ground water. The roots of the trees develop in a sufficiently deep, well-aerated layer of soil and receive additional moisture from the ground water. Of great importance is the relative stability of the ground water table, which is protected from evaporation by a substantial mantle of soil. These favorable conditions are usually reflected in an exceptionally rapid growth of timber. The composition of stands does not differ conspicuously from those growing on true upland soils, but the presence of a deep gley layer may be responsible for the occurrence of more exacting species than are ordinarily found in a given region on upland soils of similar texture. Failure to account for the gley horizon located at a considerable depth is often responsible for a gross underestimation of the potential productive capacity of forest soils (Wilde, 1929).

Figure 7–3 includes examples of soil profiles formed under the influence of the ground water table.

VADOSE SOILS

These hydromorphic upland soils are formed under the influence of precipitation water which converts the surface layer into a gley horizon. Such waterlogging or **surface gleization** is caused either by a high water-holding capacity of the surface soil or by the presence of an impervious substratum, usually a claypan.

Vadose soils are largely confined to level or nearly level areas of plateaus and broad valleys. They occur in every climatic region and on highly diversified parent materials. Depending on conditions, the composition of the surface layer of these soils is subject to wide variations: it may be covered with raw humus or a blanket of mosses, enriched in black amorphous humus, or completely deprived of dark pigments and may resemble a podzol layer. Consequently, the ectorganic, melanized, and cryptorganic phases of vadose soils of different substrata may be recognized. Some varieties of these hydromorphic "soils of the plains" (Kellogg, 1941) were described under the terms of "planosols," "pseudo-podzolic soils," "surface gley soils," "pseudo-gley soils," and "soils of amphibious development."

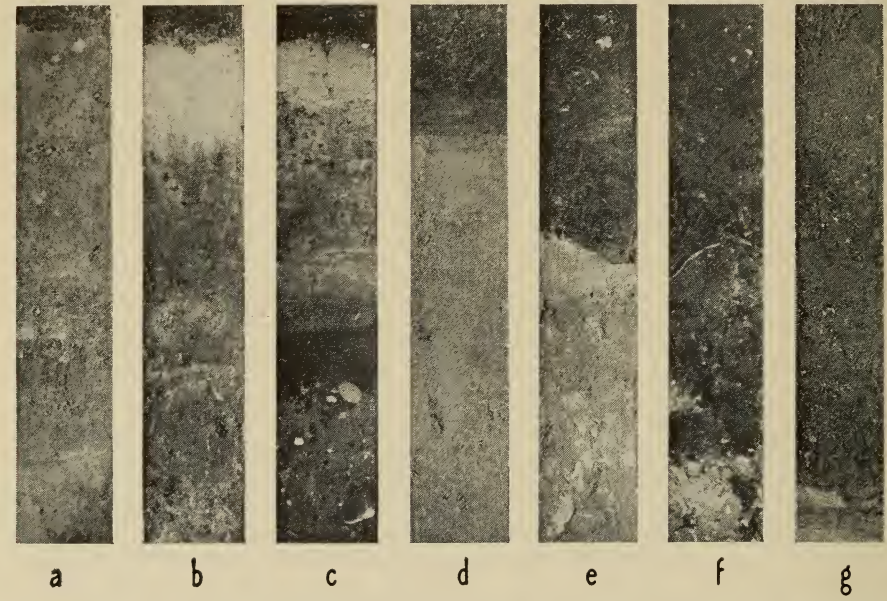


FIG. 7–3. Hydromorphic soils formed under the influence of ground water: (*a*) weakly podzolized deep-gley loam; (*b*) mid-gley loam podzol; (*c*) shallow-gley loam podzol; (*d*) alluvial sand of a stream bottom; (*e*) sapropel-like muck soil in an area subject to overflow; (*f*) sedge-wood peat of a lowmoor swamp formed on a calcareous substratum; (*g*) sedge-moss peat of a highmoor type. Note the extent of mottling in gley soils.

From a silvicultural viewpoint, the process of surface gleization attains its greatest importance within the region of podzols. In this environment the saturation of the surface soil is usually followed by an invasion of swamp vegetation and the development of peat. As often as not, peat deposits in the circumpolar tundra and taiga forests are of vadose origin. Even today the process of surface gleization annually increases appreciably the area of upland peat bogs in the region of northern forests (Hesselman, 1910; Malmstrom, 1931). The menace of the swamp encroachment is often sponsored by the removal of forest cover and subsequent increase in the amount of precipitation that reaches the ground (Tiurin *et al.*, 1935). According to observations in Canada, the formation of upland swamps takes place on most types of substrata, including those high in carbonates (Wilde *et al.*, 1954). Occasionally, waterlogged outcrops of limestone give rise to endorganic rendzinas covered with a thick mat of alkaline raw humus.

In warmer climates the surface gleization does not lead to the development of raw humus but produces soils of cryptorganic nature distinguished by a light gray surface layer over claypan substratum. These soils of the **planosol** group (U.S.D.A., 1938) occupy considerable area in midwestern United States and have a remarkable similarity to some soils of Germany classified as "pseudo-gley soils" (Laatsch, 1954). The outstanding ecological feature of planosols is that their surface gley horizon does not prevent deep penetration of roots, a condition which often permits a rapid growth of exacting mesophytic hardwoods.

Under the open stands of oak and digger pine with grass cover found in the semiarid climate of California, vadose soils develop a rich brown surface layer and may be considered as associates of melanized soils of the desert-forest transition.

Many of the tropical cryptorganic soils, described under the terms of "podzolized laterites," "podzolic red loams," and "leached red-earths," are now known to be of vadose origin (Bogatyrev, 1954). This is especially true of soils of monsoon forest where large areas of flatlands are covered with a sheet of water during the rainy season. On such areas the soils undergo "amphibious weathering" (Mohr, 1944) which produces vadose feralites with a discolored surface layer resembling a podzol horizon.

The acme in the development of vadose soils is reached in the bayous of the lower Mississippi River. These permanently flooded areas support valuable but dismal stands of bald cypress and tupelo gum whose large trunks are carried by broad bases or fluted buttresses. Mangrove thickets in salt waters of the tropics are a related type of pneumatophoric forest cover which grows on submerged substrata.

ORGANIC SOILS

Excessive moisture and subsequently deficient aeration may retard or completely arrest the activity of saprophytic organisms. Under such conditions organic remains accumulate as peat deposits that may attain a depth of many feet. At times the formation of peat is encouraged by the growth of plants whose tissues possess inherent resistance to decay. Organic deposits formed in water basins or depressions with a high ground water table are called **lowmoors** or **swamp soils**; deposits developed under the influence of atmospheric moisture above the true ground water table are called **highmoors, raised bog soils**, or **vadose organic soils.**

Lowmoor soils. These are formed throughout the forest region, largely by accumulation of plant remains in shallow lakes, ponds, and abandoned stream meanders. The process is usually initiated by reeds, sedges, and similar shoreline plants which gradually creep toward the center of the basin as their remains offer them a suitable foothold. The accumulation of debris is assisted by algae and mosses which float on the surface as consolidated layers or mats. Such mats of mosses and other water-loving vegetation may cover the lake completely and convert it into a "quaking bog" or "quagmire." The floating mat may attain a considerable thickness, become waterlogged, and sink to the bottom of the lake as an interlayer of the future peat deposit. If conditions permit, shrubs and trees invade the shore debris and floating mats, and contribute to the development of peat (Fig. 7–4). Thus, depending upon the nature of plant remains, the peat may consist of several more or less distinct layers. Lowmoor deposits in the cold and temperate regions attain a thickness of many yards; in tropics, however, their depth seldom exceeds three feet (Vageler, 1933).

In advanced stages of development, conditions of drainage, nature of the mineral substratum, and the physico-chemical properties of ground water determine the type of vegetation that occupies the lowmoor deposit and imparts to its surface layer definite morphological features. According to the predominant kind of plant remains, the lowmoor soils are designated as **sedge peat, woody peat, moss peat, sedge-moss peat**, and so forth. Sometimes the classification is more specific, and types such as *Sphagnum-Carex* peat, *Hypnum* peat, *Papyrus* peat, and cedar-fir or alder peat are recognized. Furthermore, lowmoors are classified according to degrees of decomposition of organic matter into "fine textured," "well decomposed," "fairly well decomposed," and "coarse textured" or "poorly decomposed" (Sukachev, 1923; Tacke, 1930; Dachnowski, 1933). A particularly detailed classification of peat deposits was recently reported by Kazakov (1953).

With minor exceptions, lowmoor soils exhibit similar profile patterns. Their organic surface layer (A_0 or P) grades at a certain depth into a "gyttja" (Post, 1921) or sapropel-like transitional zone of mineral soil enriched in amorphous organic matter (A_1 or M); the latter is underlain by gley substratum (G). In some cases, the organic layer rests on a calcareous substratum of marl or "bog lime" formed by precipitation from solution or by deposition of animal

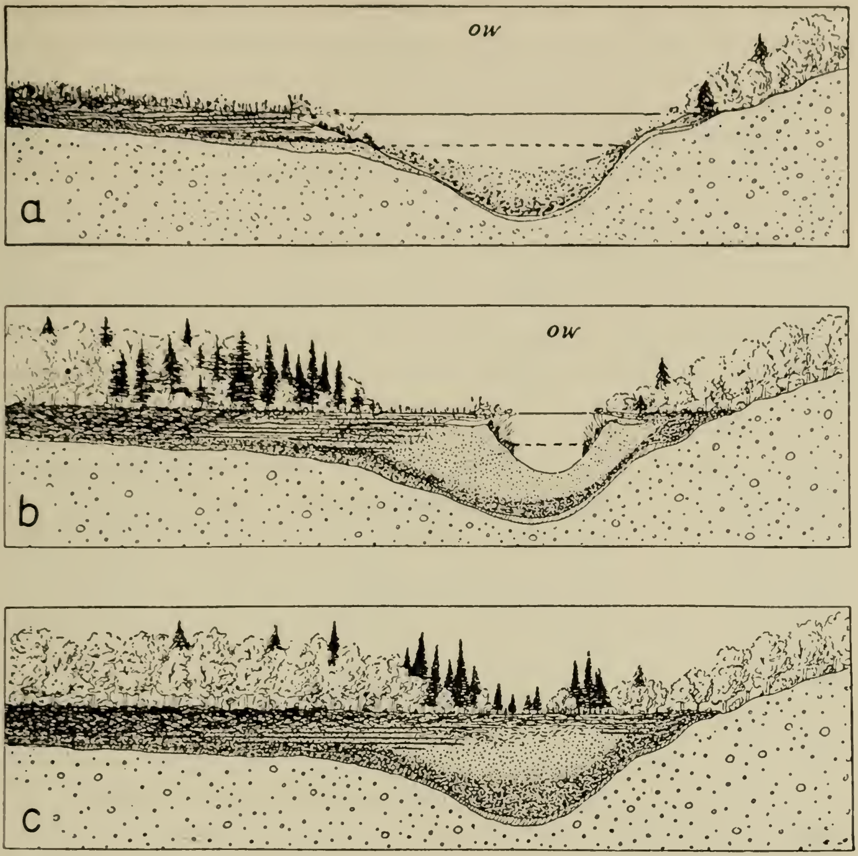


FIG. 7–4. Different stages in the development of a lowmoor peat deposit: (*a*) accumulation of aquatic vegetation in open water (OW) bordered by a marsh; (*b*) filling in of the open water by plant debris and closing in of marsh vegetation; (*c*) replacement of both aquatic and marsh vegetation by swamp forest (adopted from *Soils and Men*, U.S. Department of Agriculture, 1938).

shells. The composition of the surface holorganic layers of lowmoors is largely determined by their botanical origin and is closely correlated with the productive capacity of these soils.

The surface layer of **moss peat** is of fibrous or spongy fabric; it is free from unpleasant odors and smearing humified material. It has a brown color if derived from *Hypnum* and related mosses and is called **brown moss peat**; it is of a yellowish green color if made up of *Sphagnum* or bog moss species and is called **green moss peat.** The fragments of wood and other plant remains encountered in these deposits are only slightly altered by the processes of decomposition. The lower strata of moss peat often consist of sedges or a mixture of sedges and mosses. The forest cover includes predominantly spruce, fir, pine, and larch or tamarack; occasionally balsam poplar, aspen, white birch, and alder may also be found. Forest stands on brown moss peat, as a rule, produce much higher yields than on green moss peat; the latter at times is too poor in nutrients to nourish even the least exacting trees, such as black spruce and Scotch pine (Huikari, 1953).

The difference in the productive capacity of the two varieties of moss peat is strikingly reflected in the content of electrolytes, free oxygen, and other properties of the ground water (Pierce, 1953). The following outline illustrates the effect of the type of peat on the growth of seventy-year-old black spruce in the Algoma region, Ontario.

Type of peat	*Properties of ground water*	*Min. and max. yields (cords per acre)*
Shallow brown moss peat	pH 7.0; O_2: 3.0 ppm.; spec. cond.–0.20 mmhos.	25 to 37
Deep brown moss peat	pH 6.2; O_2: 1.7 ppm.; spec. cond.–0.11 mmhos.	14 to 20
Green moss peat	pH 5.9; O_2: 1.1 ppm.; spec. cond.–0.08 mmhos.	7 to 16
Green moss peat	pH 4.9; O_2: traces; spec. cond.–0.03 mmhos.	0 to 3

Very often the green peat represents the advanced stage of the succession initiated by brown mosses.

The development of **woody peat** is largely confined to substrata enriched in bases and areas with a slow but continuous subterranean drainage. The surface layer of this type presents a sharp contrast with that of moss peat. It consists of brown to black macerated or "putrefied" wood which is slimy to the touch, smearing, and evolves the disagreeable odor of hydrogen sulfide. Coniferous species which resist decay, especially white cedar, give rise to **coarse woody peat** whose wood fragments may be several inches long and preserve their identity. Deciduous species, such as black ash and alder, produce **fine woody peat** of highly dispersed or macerated organic matter. Forest cover on woody peat includes pure and mixed stands of a great variety of species: white cedar, balsam fir, tamarack, different spruces, black ash, elm, red maple, alder, and willows. The conifers attain rather high yields of about 20 Mbf per acre. However, the high rate of tree growth on these soils depends upon reasonably rapid movement of ground water and its degree of oxygenation.

Sedge peat is formed by remains of marsh vegetation, such as species of *Carex*, *Scirpus*, and *Typha*. It is largely confined to regions or areas precluding the growth of woody plants or mosses and frequently occurs in basins with hard ground water. Occasionally, however, sedge peat represents the initial stage in the development of moss or woody peat. Depending on the degree of decomposition, sedge peat may be of a fibrous fabric and brown color, or of an amorphous muck-like texture and of nearly black color. Sedge peat is particularly common in the prairie-forest transition where it provides nesting and feeding ground for wildlife.

In areas subject to periodic overflow, organic detritus is enriched in silt and clay particles sedimented during inundations. The resulting sapropel-like, partly mineral, partly organic deposits are called **muck soils.** In some instances, such soils are formed in grassy swamps or marshes where sedges, cattails, and reeds release in decomposition a certain amount of mineral "earthy" matter which is incorporated into the organic residue. Ordinarily the muck layer contains 20 per cent or more of mineral material. Muck soils often have a high content of nutrients, but the effects of periodic inundation and waterlogging of the surface layer considerably reduce the length of the growing season and the increment of forest stands. Many tree species inhabiting these soils, such as alder, willows, silver maple, red maple, black ash, swamp white oak, and river birch, have minor silvicultural importance even though they fulfill their essential task of water and wildlife conservation.

Moss peat derived from the green mosses of the *Sphagnum* genus has the lowest content of nitrogen and mineral nutrients; sedge peat the highest. Moss peat derived from the brown *Hypnum* mosses, and woody peat occupy an intermediate position. The composition of muck soils is influenced by the nature of sedimented material and varies within limits too wide to permit consideration of average values. *Sphagnum* peat usually has an extremely acid reaction; the reaction of other types varies from strongly acid to alkaline. Table 7–1 gives the representative chemical composition of the most important peat materials (Wilde and Hull, 1937).

Highmoor soils. In high mountains and boreal forests the invasion of *Sphagnum* mosses and other swamp vegetation takes place not only in depressions but also on upland areas. In such localities, remains of plants, chiefly mosses, accumulate to a height of several feet and rise above the neighboring ground as extensive mounds. Because highmoors are not dependent upon the occurrence of ground water, but receive their moisture from precipitation, they are also

TABLE 7–1

Total Analysis (Weighted Averages) of Moss, Sedge, and Woody Types of Peat (Wilde and Hull, 1937)

Type of Peat	O.M.	SiO_2	N	P_2O_5	K_2O	CaO	R_2O_3
				Per cent			
Sphagnum moss peat ...	97.8	0.7	0.92	0.04	0.06	0.20	0.25
Hypnum moss peat	94.5	1.5	2.09	0.06	0.08	1.00	0.60
Garex sedge peat	95.3	0.9	2.91	0.10	0.15	1.95	1.00
Woody peat	94.5	1.7	2.05	0.11	0.12	1.41	1.37

called "atmospheric swamps." Occasionally, these peculiar organic deposits develop on gentle slopes (Fig. 7–5).

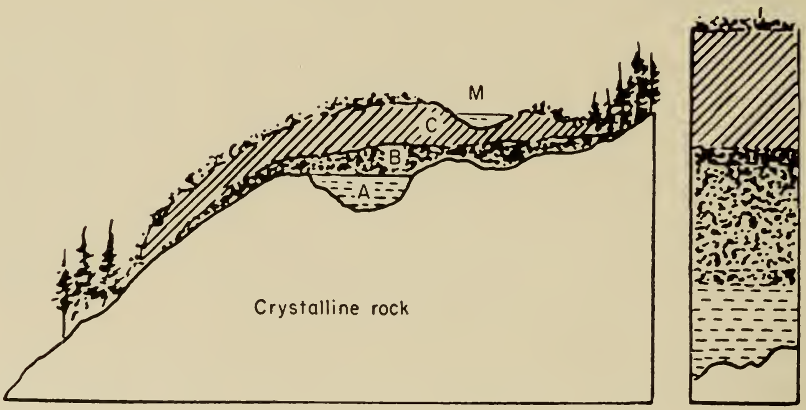


Fig. 7–5. Development of a highmoor peat deposit: pothole filled with reed peat (*A*), and covered with two successive layers of moss peat (*B* and *C*). *M* designates a "moor eye" formed by vadose water. (After H. Schreiber.)

Usually a profile of highmoor peat consists of slightly altered tissues of *Sphagnum*, compressed at a greater depth into a light yellowish brown mat. The remains of other plants, dead roots and whole stems of trees are encountered occasionally. Depending on topography and the history of the deposit, the layer of moss peat may rest on weathered rock, mottled gley substratum, a sapropel-like gyttja, or a deposit of lowmoor peat.

In high mountains, highmoors sometimes originate under forest cover and their genesis is related to the process of podzolization. The depletion of the surface layer of a forest soil in bases promotes the accumulation of raw humus which increases the water-holding capacity of soil and encourages the invasion of *Sphagnum*. In time, bog moss covers the area as a solid blanket. The insulating effect of *Sphagnum* produces a considerable difference in the summer temperature of soil and atmosphere, hindering the normal transpiration of trees. As a result, forest stands of exacting species are replaced by trees and shrubs that are adapted to the peculiar conditions of highmoor peat. The common inhabitants are black spruce, tamarack, Scotch pine, mountain pines, dwarf birch, and heath shrubs. The entire association of highmoors bears a pronounced xerophytic stamp; in fact, in some classifications highmoors appear under the designation "xerophytic swamps."

On fertile substrata the development of highmoor bog is accomplished through a long series of successional changes. In the initial stages the area is invaded by *Hypnum, Calliergon, Hylocomium,* and related mosses, which form a deposit of rich brown moss peat. In time, the fixation of nutrients by moss tissues and the increase in the content of reducing substances promote a gradual replacement of brown mosses by species of *Sphagnum.* Various members of this group complete the development of highmoor with rather amazing rapidity (Soper, 1919; Leisman, 1953). The process is accompanied by constant impoverishment of the deposit in available nutrients. The appearance of *Sphagnum fuscum* usually initiates the last act of the drama—conversion of a productive forest land into a treeless muskeg.

In advanced stages of development, highmoor peat is very strongly acid, the reaction often approaching pH 3.0; it is very low in nitrogen and mineral nutrients but has a high base exchange capacity. The excavated peat material is used for surgical purposes, as absorbent farmyard litter, for improvement of physical properties of soils, soil acidification, and as a carrier of commercial fertilizers.

8

The soil enriched in colloidal material is not a mixture of sand and clay, but a true dynamic system, for, in the words of Graham, matter in the colloidal state knows no rest.
—A. Stebutt

Physical properties of forest soils

DEPTH OF SOIL

Depth of the weathered layer and depth of the soil. The depth is a readily determinable physical property that has a decisive silvicultural importance. In regions with a prolonged drought period—for example, in California—the very existence of forest stands is determined by a certain minimum depth of the soil, such as 6 or 8 inches; on shallower regosols, the low water storage capacity permits the survival of only chaparral thickets.

In areas where rock formations are covered by a deep blanket of permeable glacial debris, loess, or fluvial deposits, the potential depth of soil usually exceeds the geotropic capacity of tree roots. Under such conditions, the soil depth is not a factor of critical importance in forest growth. The insufficiently deep soils are largely confined to geologic strata that resist weathering and are covered with a shallow regolith. Also, in mountains and hilly lands the soil depth is often reduced by continuous denudation.

These geologic limitations of the soil depth are frequently supplemented by physical, chemical, and biological conditions which preclude the penetration of root systems even in weathered material and thus restrict the actual depth of the soil. Most commonly such obstacles are presented by waterlogged gley horizons, impervious hardpans, and layers containing soluble salts in toxic concentrations. In regions affected by podzolization, raw humus may arrest the downward movement of roots and virtually limit soil depth to the surface layer of a few inches.

Classification of soils on the basis of depth. Whatever the cause, shallow depth of the soil limits the supply of water and nutrients and reduces the stability of forest stands against the wind. Considering these aspects, soils may be subdivided for silvicultural purposes into three groups: **shallow soils**, less than one foot deep; **medium deep soils**, between one and three feet deep; **deep soils**, more than three feet deep.

SOIL TEXTURE

Textural or granulometric properties of soils. Soils include two ecologically important fractions: a **coarse fraction** and a **fine fraction.** The coarse fraction, larger than 0.05 mm. in diameter, includes stones, gravel, and sand; the fine fraction, smaller than 0.05 mm. in diameter, is comprised of silt and clay. Coarse and fine fractions may be separated by shaking soil with water and allowing the suspension to settle. After about one minute, the coarse material has settled, whereas the silt and clay stay in suspension. The relative amounts of the coarse and fine soil particles determine soil texture (Fig. 8–1).

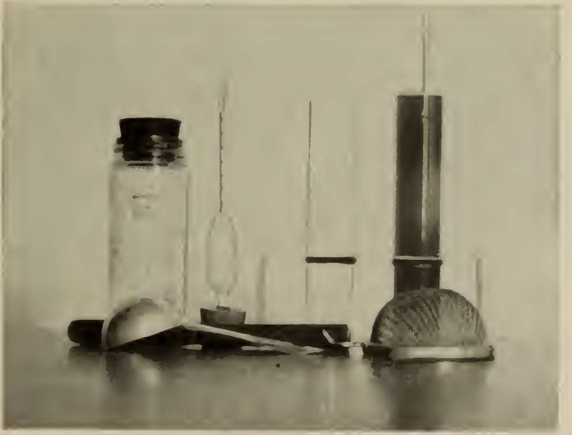


FIG. 8–1. Simple equipment for the determination of soil texture. The soil is dispersed in a 100 ml. flask and allowed to settle for 40 seconds. Then the suspension is transferred into a 60 ml. test tube and the content of silt and clay particles is determined by floating a small hydrometer.

The coarse soil material represents the "skeleton" of the soil; its function is largely limited to the physical support of plants, and it plays a minor part in plant nutrition. The fine soil material is the active portion of the soil which, through its adsorptive properties, fulfills manifold ecological functions. It is the carrier of life in the soil, or, in the words of Stebutt, it is the "soil protoplasm."

In surveys designed for agricultural purposes, classification of soils on the basis of texture is carried out in great detail. For example, surveyors of the U.S. Department of Agriculture (U.S.D.A., 1951) consider three categories of soil particles on the basis of their diameter: clay—less than 0.002 mm., silt—0.002 to 0.05 mm., and sand—0.05 to 2.0 mm. Depending on the relative percentages of these particles, soil material is then grouped into twelve major textural soil classes which are presented graphically in Figure 8–2. Sometimes these classes are further broken down into finer subdivisions. Thus, the class of sandy loam soil may be subdivided into "coarse sandy loams," "sandy loams," "fine sandy loams," and "very fine sandy loams."

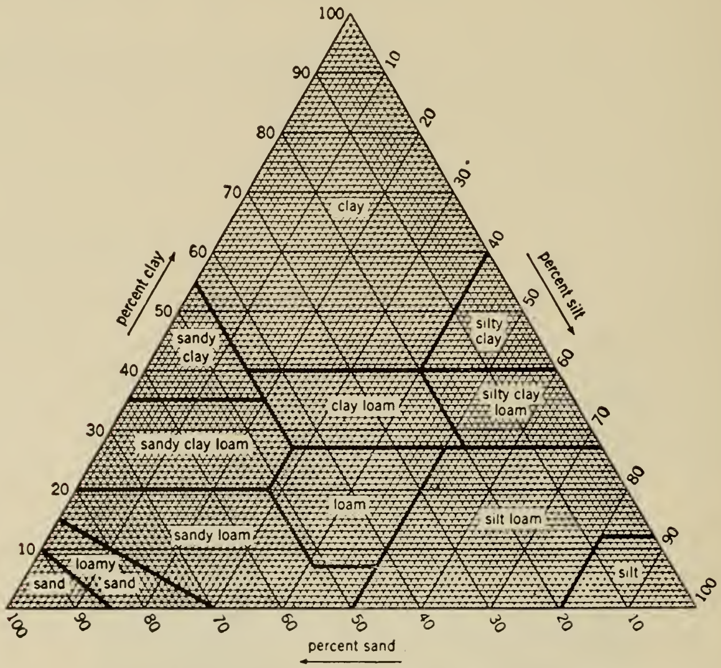


Fig. 8–2. Percentages of clay (below 0.002 mm.), silt (0.002 to 0.05 mm.), and sand (0.05 to 2.0 mm.) in the basic soil textural classes. (USDA, 1951.)

Notwithstanding the enormous importance of soil texture in all phases of silviculture, foresters can seldom make use of complicated classifications and must be satisfied in their work with a simple scheme based on the content of particles smaller than 0.05 mm. in diameter. A classification of this type, which proved in several regions to be adequate for the purposes of current forestry practice, follows:

Soil class	*Per cent of silt and clay particles smaller than 0.05 mm. diameter*
Sand	Less than 7
Loamy sand	7–15
Sandy loam	16–25
Light loam	26–40
Heavy loam	More than 40

Ecological significance of soil texture. The ability of upland soils to retain water depends largely upon the amount of silt and clay present; the greater the amount, the greater is the soil moisture content, other conditions being the same. Because the soil pores are filled with either water or air, a high moisture-retention capacity may cause inadequate soil aeration. Finally, the fine particles serve as the major source of nutrients. These effects of soil texture are frequently reflected in the composition and the rate of growth of forest vegetation (Kruedener, 1927). By and large, sandy soils support pines, red cedar, scrub oaks, and other trees which have low requirements for moisture and nutrients. Loam and clay soils usually support trees of high moisture and nutrient requirements, such as species of spruce and fir, hard maple, basswood, elm, white ash, and black walnut.

In the virgin forest, however, there may be found many instances where the correlation between soil texture and forest growth is masked by the influence of other factors, especially by the ability of forest stands to modify the environment. Through a succession of species, forest stands tend to adjust the soil conditions to the requirements of trees which compose them. For example, cut-over sandy soils of the northern United States are suited only for jack pine or red pine. After these species become established, they moderate the extremes of temperature with the canopy of their crowns and enrich the soil in organic matter, thereby increasing the retention of water and the supply of nutrients. Thus, pioneer trees create conditions for the establishment of more exacting white pine or hemlock. In a similar manner the modifying influences of other pioneer species diminish the significance of soil texture and allow more exacting climax species to succeed on soils with a relatively low content of fine particles.

Importance of soil texture in tree planting and silvicultural cuttings. In artificial reforestation, however, soils of cut-over or burned-over areas have no protection from wind and sun. Such soils are often depleted in humus and nutrients. Under these conditions, the content of silt and clay particles has a decisive influence on the survival and growth of planted seedlings.

In general, on coarse sandy soils it is advisable to plant only light-demanding pioneer pines, such as jack pine, lodgepole pine, Virginia pine, longleaf pine, and Scotch pine. Other pines, such as red pine, slash pine, and especially white pine, require loamy sand or sandy loam soils. Light loams may be reforested to coniferous and deciduous species of fairly high requirements for moisture and nutrients, namely, white spruce, Douglas fir, European larch, yellow birch, shagbark hickory, and black locust. Planting of exacting species, particularly Norway spruce, white cedar, black walnut, white ash, white oak, hard maple, and basswood, should be confined to loam and clay soils of high colloidal content.

Although there are numerous methods for the determination of soil texture, that suggested by Bouyoucos (1927) has been found as the most suitable for the needs of forestry practice. Following a procedure for rapid determination, the analysis can be completed in the field within a few minutes (Wilde, 1935; Wilde and Voigt, 1955).

Because forest soils are not always uniform in their composition, the determination of soil texture should embrace the entire soil profile to the depth of 4 or 5 feet. If the surface soil grades into coarser material, it is necessary to be conservative in the choice of trees for planting; the presence of fine-textured substratum underlying sandy soil permits greater freedom in the selection of species.

The planting possibilities depend not only on textural characteristics of soil but also on many other factors, such as the distance to the ground water table, petrographic composition of soil, and content of soil organic matter. The adaptation of species to soil also varies greatly under different climatic conditions. Therefore, the knowledge of planting possibilities is to a great extent derived from local observations of the natural distribution of trees and the growth of plantations.

Soil texture profoundly influences the technique of all silvicultural cuttings because the content of fine soil particles determines the choice of tree species which should be favored and the vigor of competing weed vegetation. On coarse-textured soils the cuttings usually aim to encourage pines, rather than oak or other exacting species; a moderate competition of weeds on these soils permits considerable opening of the canopy. On the other hand, on loam or clay soils the regeneration of exacting conifers and hardwoods dictates very conservative cuttings, precluding the suppression of natural reproduction by weeds and light-demanding sprouts.

Texture of nursery soils. The soils of forest nurseries should have an adequate content of soil colloids to insure the retention of a stable supply of water and nutrient salts. On soils with a low colloidal content, nursery stock may be adversely influenced by extreme fluctuations of moisture and nutrients even though these are supplied periodically by artificial irrigation and application of fertilizers. During hot spells evaporation from sandy soils carries unadsorbed fertilizer salts to the soil surface. In this way, the concentration of soluble salts in the surface inch may increase from about 500 parts per million to several thousand parts per million. Salts in such a high concentration often cause "burning" of the small roots of seedlings (Fig. 8–3). This effect is particularly pronounced in nursery soils underlain by a compacted, slowly permeable substratum which creates a condition similar to that of a perched water table.

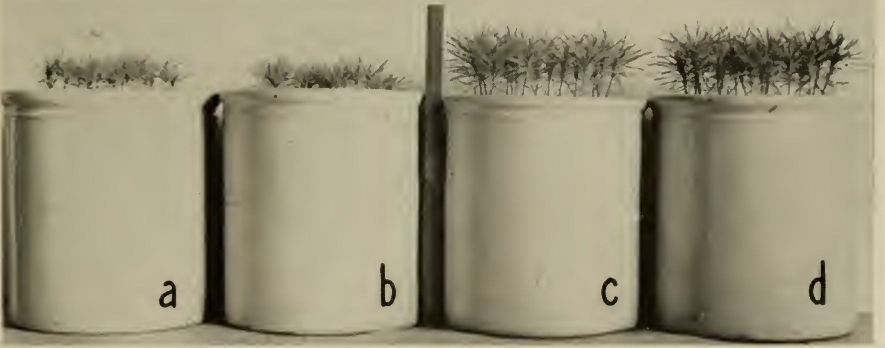


FIG. 8–3. Effect of mineral colloids on the mobility of soluble salts and growth of four-month-old red pine seedlings. (*a* and *b*) Unbuffered quartz sand treated with 1200 pounds per acre of soluble fertilizer salts whose concentration near the surface depressed the growth of trees. (*c* and *d*) Similar cultures with 10 per cent of acid-treated, nearly neutral bentonite which stabilized soil solution.

Nursery soils with a high content of mineral colloids also present serious difficulties. Fine-textured soils are usually waterlogged in the spring and late fall, and in cold regions nursery stock is damaged by heaving. Such soils may remain frozen until late in the spring and prevent lifting of stock without injury of roots. Certain complications are likely to be encountered on heavy soils in the control of parasites and in eradication of weeds.

Considering all aspects, the desirable content of silt and clay particles in nursery soils should be at least 15 and not more than 25 per cent. The adsorbing capacity of coarse-textured soils can often be increased by application of peat or clay. Heavy soils may also be improved to some extent by incorporation of organic remains, but such improvements can seldom reduce the over-all cost of stock production.

ORGANIC MATTER

Physical effect of soil organic matter. Among its numerous functions, soil organic matter exerts a purely physical influence supplementing that of mineral colloids.

Organic matter increases considerably the water-retaining capacity of soils, but this effect does not necessarily augment the supply of available water. Water is held with such tenacity by some types of organic remains, especially peat, that it is not available to plants (Feustel and Byers, 1930). Organic matter has also the ability to retain nutrients, particularly bases and ammonia. Pound per pound, the cation-adsorbing capacity of humus exceeds that of clay particles by several hundred per cent.

Upon incorporation with mineral soil, humus exerts beneficial effects on the soil structure, porosity, permeability, and aeration. It may be said that humus serves as an oiling or greasing medium facilitating the smooth performance of the soil mechanism. In the farmer's opinion, "The humus makes light soils heavier, and heavy soils lighter."

Importance of soil organic matter in reforestation. The beneficial influence of organic matter on the growth of forest plantations has been observed on numerous occasions. Nevertheless, reforestation practice of the past has generally neglected the role which humus plays in the survival and the growth of forest plantations. This indifference should be attributed to comparatively limited experience in the reforestation of old cut-over lands depleted in organic matter and the lack of a rapid method for the determination of humus content. The latter difficulty was largely removed through the development of new analytical techniques (Wilde and Voigt, 1955).

According to the results of a survey by Wilde and Patzer (1940), the height growth of jack pine plantations on sandy soils with about 1 per cent of organic matter varied between 3 and 6 inches per year;

the maximum height growth of about 15 inches per year was observed on soils analyzing at least 3 per cent of organic matter. Red pine proved to be even more exacting in regard to the soil content of humus (Fig. 8–4).

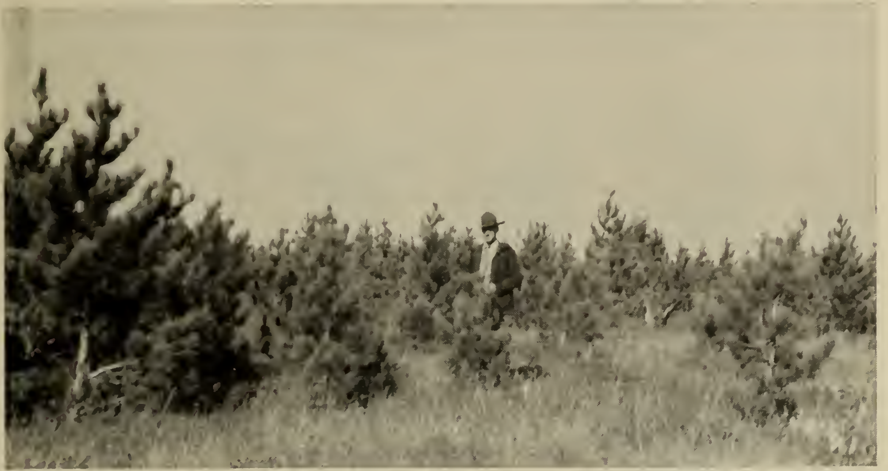


FIG. 8–4. Red pine plantation on a soil depleted in organic matter. The average height is only 9 feet at the age of 20 years.

The observations of the growth of plantations under Wisconsin conditions led to the following classification of the minimum tree planting requirements for organic matter in the six-inch surface layer: jack pine—0.7 per cent; red pine—1.8 per cent; white pine—2.5 per cent; white spruce and exacting hardwoods—4 per cent.

Because of the erratic distribution of organic matter in the soil profile, the samples for analysis must be collected by means of a tube which removes a core of the entire surface soil layer to an arbitrarily established depth, such as 6 inches.

STRUCTURE AND RELATED PHYSICAL PROPERTIES OF SOILS

Types of soil structure. Soil structure is defined as the arrangement of individual soil particles (Baver, 1956). If soil particles are not aggregated, the soil is said to have a **simple structure**; if aggregated, the soil has a **compound structure.** The formation of structural aggregates is caused by the action of electrolytes, organic matter, mineral colloids, freezing and drying, growth and decay of roots, consumption of carbonates by roots, and the activity of soil organ-

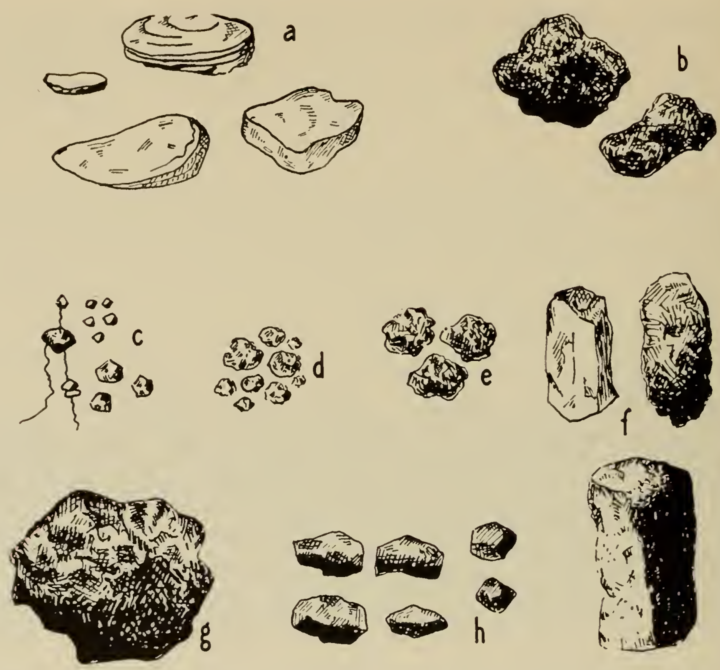


Fig. 8–5. Types of structural aggregates occurring in forest soils: (*a*) platy; (*b*) lumps; (*c*) granular; (*d*) fine crumbs; (*e*) coarse crumbs; (*f*) columnar; (*g*) clods; (*h*) nutlike.

isms. The combined effects of these factors produce highly diversified structural patterns of soils that can be expressed by a score of more or less appropriate terms (Russell, 1950). Considering the limitations of purely descriptive ratings, classification of structure of forest soils may be reduced to the following distinct types (Fig. 8–5):

Single-grained: an incoherent condition of the soil mass with no arrangement of the individual particles into aggregates; predominant in soils of sandy texture.

Massive or puddled: a compacted or cemented condition showing no evidence of any distinct arrangement of the soil particles; common to podzols and inadequately drained soils. In some instances puddled structure is a result of grazing, use of motorized logging equipment, or prolonged cultivation.

Laminated or platy: aggregates form fairly hard, horizontally oriented plates $\frac{1}{16}$ inch or more in thickness; common in podzolic and strongly leached prairie-forest soils.

Crumby: aggregates of irregular shape, of a medium to soft consistency, $\frac{1}{8}$ inch or larger in diameter; characteristic in humus layers of the mull type, especially those formed by earthworms.

Granular: aggregates of more or less subangular or rounded shape, of medium consistency, varying in size up to 1/4 inch in diameter; common in humus layers of mull type, especially in those associated with brownearth soils.

Blocky or **nut-structured:** compact aggregates, more or less rounded in shape, of medium to hard consistency, varying from 1/4 to 1 inch in diameter; outstanding in prairie-forest or grood soils and soils of calcareous substrata.

Columnar or **cloddy:** aggregates of irregular shape, of medium to hard consistency, 1 inch or larger in diameter; confined mainly to the deeper layers of fine-textured soils and alkali soils.

Effect of soil structure on forest growth. The structure of soils may greatly modify the ecological effects of soil texture. Within certain limits the macroscopic structural features of forest soils indicate the infiltration capacity and aeration of the soil and its predisposition to root penetration. Soils of massive or puddled structure may hinder the growth of trees in several ways. Such soils may not be readily permeable to rainwater and may lose a considerable amount of moisture through evaporation or runoff. On the other hand, puddled soils may become waterlogged, with their air content reduced below the critical level needed for satisfactory growth of certain tree species. For this reason, soils of a massive structure are often inhabited by conifers of saprophytic traits. The roots of these trees remain largely within the surface layer of raw humus and thus partly avoid the ill effects of poorly aerated substrata.

Fine-textured soils with a pronounced blocky structure, particularly calcareous clays, may also exert an unfavorable influence on the growth of forest stands. Profiles of these soils in time of drought reveal many dead rootlets which perished in large interstices. Moreover, the crevices created by the shrinkage of the clay soil promote a too rapid, wasteful percolation of water. As a result, deforested areas of structured calcareous clays are often invaded by drought-resistant pines rather than mesophytic species, a phenomenon usually uncommon to other fine-textured soils of temperate regions (Wilde, 1932). It may be surmised, therefore, that the formation of hard aggregates imparts to some clay soils the properties of sandy or gravelly soils.

The judgment of the structural properties of forest soils solely on the basis of ocular examination may be grossly misleading because some soils owe their satisfactory physical properties to concealed microaggregation. An enormous area of podzolized, cryptorganic, and vadose soils of apparently massive structure is occupied by highly productive stands of exacting tree species, conifers as well as hardwoods. Therefore, an appraisal of the morphology of soils, particularly those of cut-over lands, may occasionally require microscopic examination, as suggested by Kubiena (1948), or the use of suitable physical analyses.

Bulk density of soils. Within the same textural class, structural properties are correlated with the oven-dry weight of a unit volume of soil, referred to as **bulk density, volume weight,** or **apparent specific gravity.**

For determination of the bulk density, soil samples are collected by means of a special sampling cylinder, with all precautions taken to avoid disturbing the natural structure. The sample is dried at 105° C., and its weight in grams divided by volume in cubic centimeters gives the bulk density. The bulk density of forest soil varies from 0.2 in ectorganic layers to nearly 1.9 in coarse sandy soils. Compacted soil layers whose bulk density exceeds 1.75 for sand and 1.55 for clays may prevent the penetration of roots (Veihmeyer and Hendrickson, 1948). In many instances, bulk density is correlative with porosity, degree of aeration, and infiltration capacity of soil.

Bulk density acquires particular significance in the determination of soil nutrients and other chemical constituents. Analysis of soil establishes the relative weights of different nutrient elements or compounds found in pulverized soils. Such results do not present the actual amount of nutrients found in the soil until they are recalculated on the basis of bulk density of the plowed layer or of different soil horizons. In agronomical practice this is usually accomplished by assuming that the plowed layer of cultivated silt loam soils weighs 2,000,000 pounds per acre, whereas a similar layer of sandy soils weighs 2,400,000 pounds per acre. These figures, of course, are a gross approximation, but considering that cultivated soils are largely pulverized by tillage, the generally accepted practice provides reasonably satisfactory results.

The situation is entirely different in dealing with forest soils that have not been touched by the plow. The bulk density of crumb-structured and massive-structured silt loams may show a difference of more than 100 per cent. Under such conditions, the knowledge that a certain soil material has 0.2 per cent of total nitrogen or 100 ppm. of available potassium is meaningless unless the weight per volume unit of this particular material in its natural state is known.

In spite of its indisputable importance in soil management and the simplicity of its determination, bulk density is the factor that is most sadly neglected in analyses of forest soils.

Soil porosity. The porosity is determined by the space in the soil body not occupied by solids. Therefore, pore space (P), expressed in per cent by volume, is calculated from the real specific gravity of soil (S) and its apparent specific gravity or bulk density (D).

$$P = 100 \times \frac{S - D}{S}$$

Porosity of forest soils varies from 30 to 65 per cent. The coarse-textured soils usually have less pore space than fine-textured soils because of their smaller surface area and closer contact of the particles. However, puddled loam or clay soils may have a porosity lower than that of sandy soils (Auten, 1933).

Depending on the size of the pores, soils of the same pore volume may exert essentially different influence on forest growth. If soil has a preponderance of small or "micro-pores," it is likely to have a high moisture-retention capacity and a tendency to become waterlogged. Conversely, if soil has a preponderance of large or "noncapillary" pores, it will possess a high aeration as well as infiltration capacity. The smaller noncapillary pores, however, are responsible for temporary retention or "detention" (Lassen *et al.*, 1952) of a considerable fraction of gravitational water.

Soil aeration. The pore space is occupied by water and air; hence the porosity (P) and the volume of water, expressed on a percentage basis (W), determine the percentage of soil aeration (A):

$$A = P - W$$

It has been observed in several studies that the air content of soil influences the distribution and growth of forest vegetation (Burger, 1922; Němec and Kvapil, 1925). The deficiency of air is usually reflected in an abnormal, nearly pathological development of root systems (Fig. 8–6). In soil analyses it is common to determine the so-called "absolute" air capacity, or the amount of air which is present in a soil after it has been saturated with water and allowed to drain for 24 hours. On this basis most upland plants require for satisfactory growth an air content of soil not lower than 10 per cent by volume (Kopecký, 1914; Stephenson and Schuster, 1937). Rapidly growing stands of Norway spruce, however, were observed on soils with an absolute air capacity as low as 5 per cent (Wilde, 1929). Certain hardwoods, such as hard maple, white ash, and basswood, require a much higher degree of soil aeration, for the air capacity of upland soils supporting rapidly growing hardwood stands rarely falls below 15 per cent. Figure 8–7 illustrates the proportion of

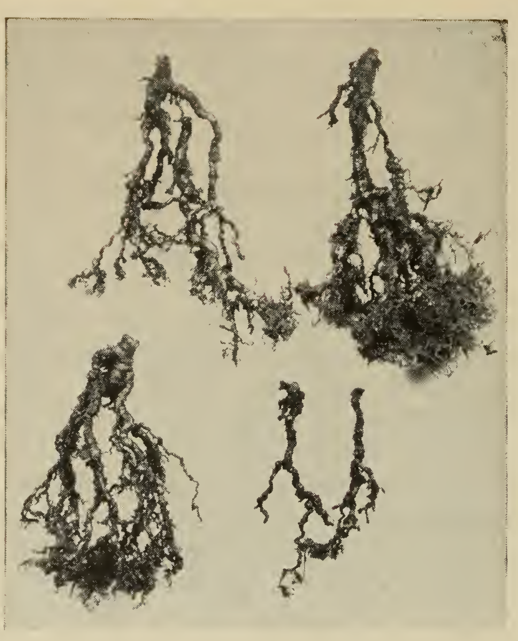


Fig. 8-6. Abnormal morphology of roots of trembling aspen developed under the influence of inadequate aeration. Trees are growing on a shallow-gley sandy soil underlain by the ground water table at a depth of about a foot. (After G. K. Voigt, 1951.)

solids, water, and air generally found in forest soils of different texture.

Soil aeration attains its utmost importance in nursery beds supporting dense stands of seedlings. The air content of such soils should not be permitted to decrease below 20 per cent for a period exceeding a few hours.

Poor soil aeration is at times alleviated by the effect of oxygenated rain or ground water. Some field crops, particularly cotton, can grow

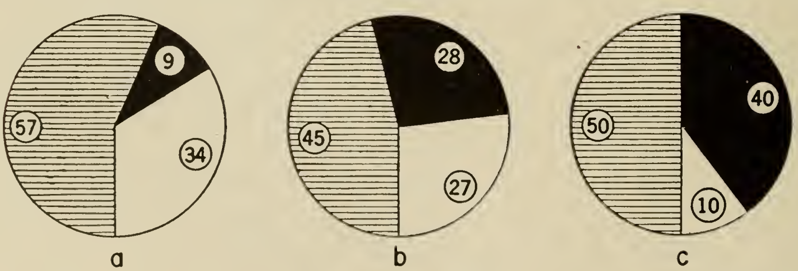


Fig. 8-7. Relative contents of solids (cross-hatched), water (shaded), and air (white) in different forest soils at a depth of 2 feet: (*a*) outwash jack pine sand; (*b*) nut-structured morainic silt loam under oak and hickory; (*c*) podzolized lacustrine clay supporting white spruce and balsam fir.

satisfactorily in completely saturated soils, provided there is an inflow of oxygenated water (Woodburn, 1945). Trees on stream-bottom soils with sufficient subterranean drainage show rapid growth even though their root systems are completely submerged in water (Clements, 1921; Pierce, 1953).

Air and water permeability of soil. The insufficient **air permeability** of soil, especially of its very surface layer, may be caused by a number of conditions, such as trampling by grazing livestock, prolonged cultivation, overwash of eroded clay, impact of raindrops, or use of heavy logging machinery (Steinbrenner and Gessel, 1955). According to Free *et al.* (1940), a few trips across the land with an empty truck can reduce the pore space from 53 to 40 per cent.

Because of the respiration of roots and soil organisms, the air of the soil is constantly enriched in carbon dioxide. Therefore, if the diffusion of gases is impeded by an impervious layer, the CO_2/O_2 ratio may rise to a level harmful to tree roots (Romell, 1922). The air permeability of soil may be determined by means of the manometric soil air permeameter (Janert, 1937; Wilde and Voigt, 1955), as illustrated in Figure 8–8, or it can be inferred from the bulk density and porosity of the soil.

The **water permeability** or **infiltration capacity** is closely related to the air permeability, aeration capacity, and porosity of soil. According to observations of Burger (1929) a soil with an air capacity of 17 per cent, supporting a rapidly growing forest stand, infiltrated 10 cm. of water in about 2 hours; an unproductive soil with an air capacity of 5 per cent infiltrated the same amount of water in 45 hours.

If the very surface layer of soil is sealed and cannot infiltrate water, the permeability of the lower part of the soil profile is of little significance. A conspicuous illustration of such a condition can be observed in grazed woodlots on soils of the prairie-forest transition (Steinbrenner, 1951). The trampling of livestock compresses the surface 2-inch layer to such an extent that nearly half of the precipitation is lost through runoff or evaporation. The high permeability of the nut-structured *B* horizon in this case serves little useful purpose.

A contrast in infiltrating capacity of the soil is presented by some fine-textured crumb mull soils in the podzol region. The high permeability of the aggregated surface layer rapidly decreases in the *B* horizon which at the depth of about 2 feet exhibits the mottling of reduced compounds. In spite of the abundant population of earthworms and high content of incorporated organic matter, the soils of

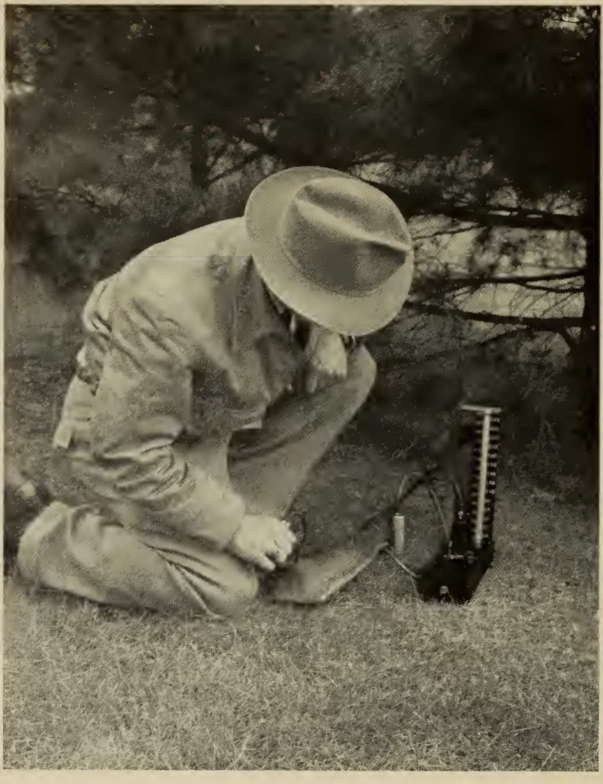


Fig. 8–8. Taking the "blood pressure" of soil—a rapid determination of air permeability of the soil by the use of a sphygmomanometer.

this morphology support slowly growing and fungi-infested stands of deciduous species. Therefore, in some instances, the investigation of the soil infiltration capacity should be extended to the depth of 3 or 4 feet.

If the soil is located on a slope of considerable gradient, the occurrence of the impermeable layer is likely to have a less detrimental influence because the surplus of gravitational water is usually discharged in the form of subterranean runoff. In sandy soils the impeded water permeability of the compacted *B* horizon, or so-called "fragipan" layer, increases the supply of soil water and often stimulates the growth of aspen and conifers (Wilde, 1950).

Penetrability of soil. The resistance offered by soil to the entrance of a solid body, such as a metal rod, is related to textural and structural characteristics and the content of soil moisture. In surveys of some soils the resistance of soil to the core-sampling tube helps to detect the depth to the compacted or cemented *B* horizon, a feature of considerable importance. In most cases, however, the determination of the penetrability by pressure-recording instruments is impractical in investigations or management of forest soils.

Several other characteristics of soils, such as consistency, cohesion, and plasticity deserve to be recorded in the description of soil profiles by appropriate terms, such as mellow, friable, compacted, indurated, cemented, plastic, and sticky. The expression of these conditions in terms of concrete analytical data, as suggested by some agronomists, is seldom required in silvicultural practice.

SOIL WATER

Ecological significance of soil moisture. Soil moisture is one of the most conspicuous ecological factors. Seeds or fungus spores may remain dormant in dry soil for thousands of years until a few drops of water initiate the process of cell division. The lack of water terminates the life of plants in a more dramatic manner than any other natural cause. Besides its direct influence on the growth of plants, the amount of soil water predetermines a number of other important soil conditions, namely, soil temperature, aeration, microbiological activity, availability of nutrients, and concentration of toxic substances. Yet, in spite of these far-reaching influences, soil moisture cannot be singled out as "the most important" ecological factor, an expression so often met in forestry literature. The normal development and even the very life of any organism depend upon the satisfactory level of all growth factors. The optimum content of soil water may be rendered totally useless for plant growth by a deficiency of 0.01 g. of boron per cubic foot of soil or by a critical state of any other soil property.

The neglect of the co-influence of oxygenation, content of nutrients, and concentration of toxic substances led in the past to many unqualified generalizations of the effects of soil moisture and to gross errors in classification of forest habitats which are only now fully realized by foresters (Pogrebniak *et al.*, 1944). On the other hand, the problem of soil water has gradually become complicated by many agronomical concepts which are inapplicable to forest soils. Therefore, the available information on the ecological effects of soil moisture must be subjected to meticulous scrutiny before it can be accepted by silviculturists.

Considering the water regime, soils fall into two major groups: **upland soils** in which root systems are not in contact with the fringe of the ground water table, and **lowland soils** in which root systems are influenced by ground water. The recognition of these two groups of soils is of cardinal importance because many soil properties that regulate the growth of trees in upland soils lose their significance in soils underlain by subterranean waters.

WATER RELATIONS IN SOILS NOT INFLUENCED BY GROUND WATER

Forms of soil water. Not all the water which soils receive from precipitation, condensation, runoff, and seepage is utilized by plants, for some of the water is lost from the root zone through evaporation and percolation. This loss of moisture is to some extent moderated by the adsorbing capacity of soil, a property determined by the size of soil pores and soil particles and by the nature of mineral and organic colloids. The forces of **adhesion, cohesion,** and **surface tension** exerted by the soil regulate the relative mobility of soil water and in turn differentiate the liquid phase of the soil profile into three more or less distinct fractions: **gravitational water** which moves through large pores under the force of gravity; **capillary water** retained in small micro-pores and on the surface of soil particles; **hygroscopic water** held very firmly by adhesive forces as a thin film surrounding the soil particles (Fig. 8–9).

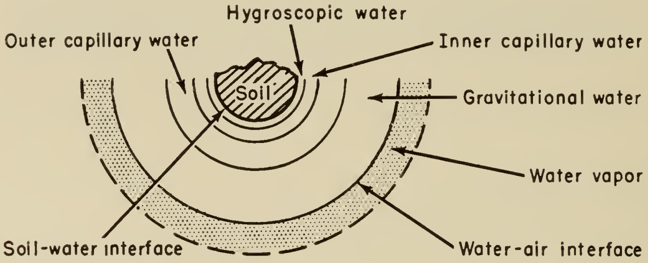


Fig. 8–9. Schematic presentation of different forms of soil water.

There is nothing known about the origin of either the force of gravity, causing the downward movement of water, or the adhesive and cohesive forces responsible for the adsorption of water molecules. In all probability these forces are related to electromagnetic or electrostatic phenomena, but today, as nineteen centuries ago, no scientist can disagree with St. Paul's statement that the world was created "out of things which do not appear" (Barnett, 1952).

In spite of this, the energy with which water is held by soil particles and in soil pores can be measured in a simple manner by applying suction or pressure to a sample of saturated soil placed over a permeable membrane. The suction necessary for the removal of a certain portion of water can be expressed either in atmospheres or in the height of a water column. By analyses of this kind it has been found that all the gravitational water can be removed from the soil by a suction of about $^{1}/_{3}$ atmosphere, that is, 250 mm. of a mercury column or about 340 cm. of a water column. On the other hand, molecules held by adhesion on the surface of soil particles can be removed only by a tension exceeding 1000 atmospheres, or 1,000,000 cm. of a water column.

To avoid cumbersome numbers Schofield (1935) suggested the use of the pF value, which is the logarithm of the "capillary potential" or the tension of a water column. If the water is held with a tension equivalent to that of a column of water 1000 cm. high, the capillary potential is pF 3.0. The tension of 10,000,000 cm., or pF 7, corresponds to the maximum theoretical force with which water molecules are retained by soil. The pF of free or ground water is zero. The boundary between capillary water and the gravitational water lies in the proximity of pF 2.5. The tension of pF 4.2 supposedly signifies the wilting point, or the critical content of water at which plants wilt. A silt loam and a sand with a moisture content of 15 per cent are likely to have pF values of 4.0 and 2.0, respectively (Fig. 8–10).

The gravitational, capillary, and hygroscopic water perform essentially different functions in the soil. Even within each of these groups the behavior of water is regulated by the magnitude of tension forces. For example, the outer capillary water, held at a tension of pF 3.0, is more available to plants than the inner capillary water, held at a tension of pF 4.0.

Gravitational water. The gravitational water fills the noncapillary pores of the soil larger than 0.05 mm. in diameter; it drains readily under the influence of gravity and is largely responsible for the translocation of soluble salts and colloids.

Gravitational water is readily available to plants but its degree of utilization varies depending upon the time of the year and the depth of root penetration. When vegetation is dormant or in soils supporting shallow-rooted species, such as spruce, most of the gravitational water percolates through the soil profile to the ground water. During the growing season, however, much of the gravitational water is intercepted by root systems, especially when they extend to a depth exceeding twenty feet. According to Wittich (1938), the rate of percolation of water in outwash sand is about 0.4 inch per hour. At this rate of discharge a considerable fraction of gravitational water

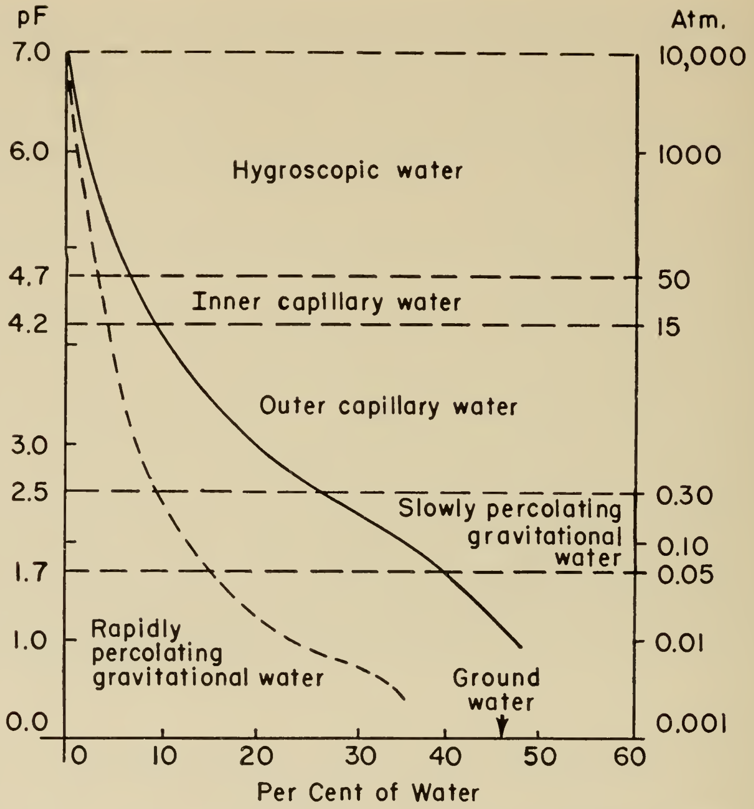


FIG. 8–10. Tension curves for an outwash sand (broken line) and morainic loam (solid line). Figures on the right side indicate approximate tension forces in terms of atmospheres.

may be utilized by the deep root systems of forest stands. In loessial silt loam soils the rate of percolation was found to be much slower, and hence the loss of gravitational water in deep, fine-textured forest soils is of little practical significance. The idea that available water does not include gravitational water has no foundation in regard to forest vegetation, especially that of phreatophilic species.

In soils permeable only with difficulty, gravitational water may adversely influence the growth of forest stands by hindering respiration of roots of phreatophobic trees.

Capillary water. After all gravitational water has drained away, the soil retains water on the surface of soil particles and in the small capillary pores or interstices. This water is held by **adhesion**—attraction between water molecules and soil particles—and by **cohesion**—attraction between water molecules themselves. The retention of water is directly proportional to the specific surface area of soil particles and inversely proportional to the diameter of soil pores. Therefore, fine-textured soils possess a high water-retention capacity. This is particularly true of soils enriched in clay minerals that exhibit a lattice structure and a very large internal surface. Also, peat with its spongy structure can adsorb water greatly in excess of its own weight.

The energy of water retention decreases with the distance from soil particles or the walls of the interstices. At a certain point the retention energy becomes so low that the boundary between the capillary and gravitational water is reached.

Capillary water may move under the influence of the capillary gradient from a region of lower tension to that of higher tension, that is, from a moist to dry portion of the soil. The capillary movement helps to maintain a uniform distribution of moisture in the soil profile, for it may be in any direction, even against the force of gravity. The upward movement is usually induced by evaporation from the surface soil and by the drying action of roots. The rate and distance of the movement of suspended water depends upon the degree of soil saturation, the texture and structure of soil, and conditions of the atmosphere. The movement is much slower in stiff clays than in sandy soils, but the opposite is true in regard to the distance of movement (Wollny, 1884). Within certain limits capillary movement may benefit the growth of trees by supplying water to the roots from the deeper soil layers; it may also cause a loss of water due to evaporation from an exposed soil surface (Fisher, 1923; Keen, 1931). In time of drought, the capillary transfer of water from the moist to dry region of the soil is too slow, and the utilization of the stored capillary water is accomplished by the rapid growth of rootlets or mycorrhizal mycelia toward the available water, rather than by the movement of water toward the roots (Rotmistroff, 1926; Laatsch, 1952).

Occasionally the downward movement of the capillary water may be arrested by a gravelly or sandy substratum underlying a fine-textured soil. This happens largely because of the difference in tension forces of the two layers and a subsequent break in the capillary gradient. In the absence of a network of root systems the water may accumulate above the coarse layer in a quantity sufficient to cause partial deoxidation, suggesting the development of a mottled gley horizon. This phenomenon may also be explained on the basis of the electrodynamic theory of Vageler (1932) who maintains that the retention of the capillary water is due to electric charges of swarm ions and is not influenced by the force of gravity.

The greater portion of the suspended or nongravitational water is available to plants and it represents an important reserve supply of moisture on which plants can draw in the inter-rain periods. At a certain distance from the air-water interface, however, the "inner capillary water" is held with a tension exceeding the absorptive power of root systems.

Hygroscopic water. Dry soil traps water molecules from the air until an equilibrium is established between the soil and the atmosphere. The water molecules are held on the surface of soil particles as well as in the micro-pores of the soil colloids. Because it is impossible to subdivide the processes of condensation and adsorption, in the opinion of Russell (1950) the concept of hygroscopic water lacks theoretical foundation. Nevertheless, it is common in soil physics to apply the term "hygroscopic water" to the tightly held fraction of water that is retained by oven-dry soil in an atmosphere of 99 per cent relative humidity and a temperature of 30° C. This fraction has a negligible mobility in liquid form and can be driven off only by a temperature exceeding the boiling point of water or by a low air humidity. Otherwise, the thin film of condensed water cannot be withdrawn by forces which are measured in scores or even thousands of atmospheres and which by far exceed the absorbing power of root systems.

Because the surface area of soil is inversely proportional to the size of soil particles, fine-textured soils hold a larger amount of hygroscopic water than do the coarse-textured soils. Based on this relationship, the maximum content of hygroscopically bound water was used by Mitscherlich (1923) as a measure of the soil colloidal content and as an index of the "physiological dryness" of soil.

Soil moisture constants. The adsorbing capacity of soil is responsible for two diametrically opposed processes which determine the content of available water. It reduces the loss of water through percolation and provides the supply of moisture to plants during precipitation-free periods; it deprives plants of a certain fraction of water by holding water at a tension exceeding the absorbing power of roots. An expression of both the useful and harmful adsorbing effects of soil is often attempted through analytical determinations of the so-called "moisture constants," such as **absolute water-holding capacity, field capacity, moisture equivalent, hygroscopic coefficient,** and **permanent wilting point.**

As pointed out by Richards and Wadleigh (1952), "Most of these terms are concerned with hypothetical concepts or with measurements made in accordance with standardized procedures and are not readily identified with the physical properties of the soil or water." This statement is especially true of soils supporting forest vegetation. The following brief review of common moisture constants is made in the light of silvicultural practice.

Absolute water-holding capacity refers to the percentage of water by volume retained by a soil after it has been saturated and then allowed to drain for a period of 24 hours. This content of water is usually determined by an analysis of samples collected by means of steel cylinders (Fig. 8–11). It provides only an approximate picture of soil retention capacity because not all soils lose their gravitational water in the prescribed period of 24 hours. Moreover, the rate of drainage in an isolated small sample is essentially different from that in the undisturbed soil profile. In spite of these shortcomings, experience of many years has demonstrated that the determination of the absolute water-holding capacity has definite value in agricultural and silvicultural practice (Kopecky, 1928; Němec and Kvapil, 1925). Analysis of this kind helps the regulation of artificial watering in nursery soils of a low porosity and aeration capacity.

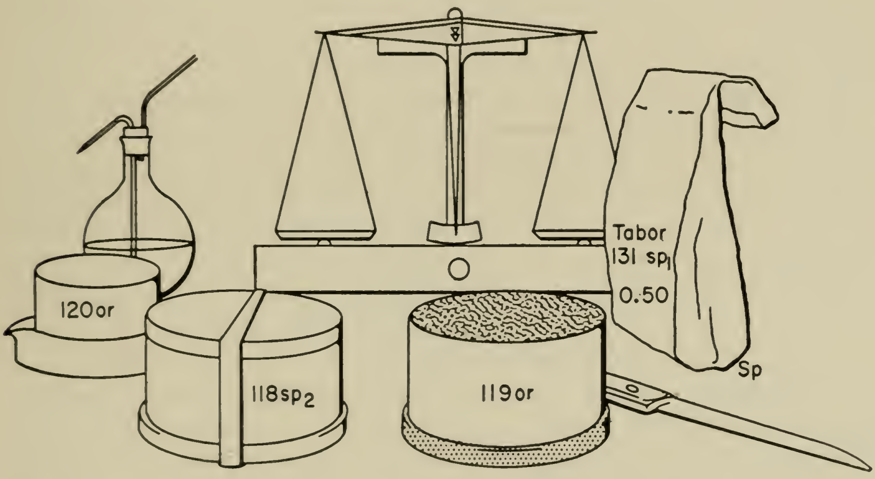


Fig. 8–11. Equipment used in the determination of the absolute water-holding capacity on samples of soil collected by the use of steel cylinders. (After Kopecký, 1928.)

Field capacity, according to Veihmeyer and Hendrickson (1931), refers to "the amount of water held in the soil after the excess of gravitational water has drained away and the rate of downward movement of water has materially decreased." This is a rather vague concept that is not in the spirit of analytical precision. Moreover, the determination of this soil characteristic requires repeated analyses extended over a period of two or three days, a task few men of practice can ever undertake. Considering practical aspects, the field capacity should be synonymous with the absolute water-holding capacity and express the content of water retained by the soil after 24 hours of drainage.

Moisture equivalent, introduced by Briggs and McLane (1907), expresses the amount of water held in the soil sample after it has been subjected by centrifuging to a force of 1000 times that of gravity. This content of water is determined on a small sample of sieved soil, that is, by a method totally inadequate in analyses of forest soils. The moisture equivalent in some instances coincides with the field capacity of the plowed layer, homogenized by cultivation, but is in no way related to the water-holding capacity of forest soils in their undisturbed state.

Hygroscopic coefficient, or the content of hygroscopically bound water, is another perennial of textbooks on soils that is rated among soil moisture "constants." It was originally claimed by Mitscherlich (1923) to represent the fraction of soil water unavailable to plants. However, the values of the hygroscopic coefficient proved to be uncertain because of **hysterisis,** a phenomenon which modifies the moisture content of a soil in equilibrium with a given vapor pressure. A soil that attained equilibrium in the process of drying invariably contains a higher percentage of hygroscopic moisture than a soil which has reached equilibrium in the process of water adsorption. Research of Keen (1931) and Olmstead and Smith (1938) led them to dismiss the hygroscopic coefficient as a hypothetical value without practical importance.

Wilting coefficient or **permanent wilting point** is a moisture constant which was intended to express the water content of soils at which plants, such as sunflowers, permanently wilt. A knowledge of this critical content of soil water is required in only the very few instances where forestry practice is confronted with highly colloidal clay soils. Such soils have a very large specific surface and a high percentage of the hygroscopic and inner capillary water which is unavailable to plants. Therefore, nursery stock or field planted seedlings of high moisture requirements may perish from drought even though the soil contains 10 per cent or more water on oven-dry basis. The damages of this kind are often aggravated because the water of light rains may be wholly intercepted by the surface clay layer and fixed in unavailable form (Pearson, 1931; Scholz, 1935). Hence, soils of a high wilting coefficient require increased attention in artificial watering of nursery stock and elimination from field planting of the drought-vulnerable species with slowly growing root systems, particularly spruce.

An accurate determination of the wilting coefficient requires prolonged and complicated greenhouse or field studies employing living plants. Therefore, attempts were made to determine the wilting coefficient indirectly by dividing the moisture equivalent by 1.84, an approximation which failed to yield satisfactory results; the conversion factor actually was found to vary from 1.5 to 5.6 (Duncan, 1939). Consequently, soil specialists returned to the determination of the wilting coefficient by direct tests of plant behavior, a technique which is seldom within the reach of a forester. At the present state of knowledge, the best solution of the problem is offered by the determination of water retained at a tension of 15 atmospheres, as recommended by Richards and Wadleigh (1952). In the absence of suitable pressure membrane equipment, the fraction of unavailable water may be roughly estimated from the content of clay particles. The content of unavailable hygroscopically bound and inner capillary water in coarse sandy soils, amounting to about 2 per cent, is too small to justify its determination.

It cannot be stressed too emphatically that the determination of soil moisture constants in silvicultural work must be preceded by a careful investigation of the hydrological features of the soil and the extent of root penetration. If the soil is underlain by a ground water table or is influenced by an extended capillary fringe or seepage, the determination of moisture constants may not serve any useful purpose. On the other hand, the root systems of deep-rooted trees may reach a depth of 25 feet or more and attain the total length of several hundreds of miles (Bühler, 1922; Matiuk, 1955). The enormous ability of such roots to utilize water of the lower horizons renders meaningless the determination of moisture constants in the surface soil layers. Even trees of young orchards exhibit a considerable ability to cope with a critical content of moisture. According to Veihmeyer's observations (1927): "Apparently the roots of these trees were able to obtain water as readily whether soil moisture had been reduced almost to the wilting coefficient as when soil was filled with water to its maximum field capacity . . . While these results apply only to the young prune trees, it appears that many of the current views regarding soil-moisture relations of other plants may also be questioned."

If conditions call for a detailed investigation of the soil moisture relations, it is best to undertake a systematic analysis of the entire root-bearing zone, as exemplified by the work of Veihmeyer and Hendrickson (1942). In recent times there have been introduced several methods of tensiometric and electrometric determinations of soil moisture content *in situ* which facilitate insight into the water regime of soils supporting forest and orchard trees (Remson and Fox, 1956). However, unless such determinations are performed with expert knowledge of technique, erroneous results are to be expected. On the other hand, the research of Wissotzky (1930) and other investigators demonstrated that simple gravimetric determinations of the water content in soil profiles provide a revealing picture of soil moisture conditions influencing forest growth (Fig. 8–12).

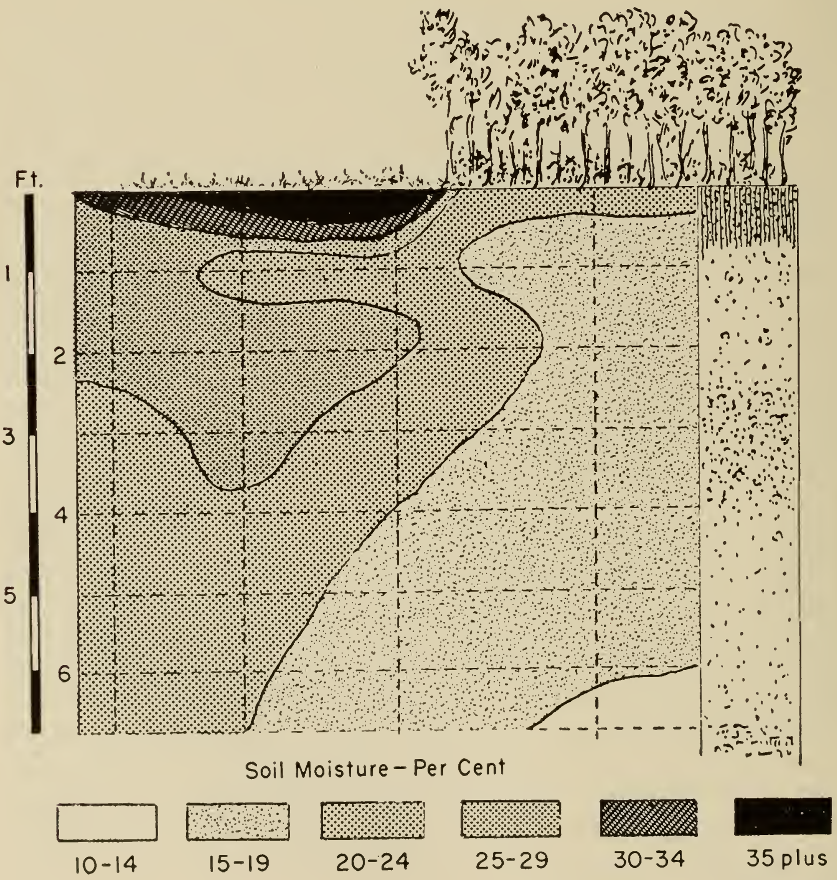


FIG. 8–12. Distribution of moisture under a mature stand of hardwoods and adjacent cut-over area in the middle of September, 1899. (After Wissotzky, 1930.)

WATER RELATIONS IN SOILS INFLUENCED BY GROUND WATER

The nature of ground water. For many centuries the origin of ground water was attributed to infiltration. Marcus Polius, a Roman scientist, stated in "De Architectura" that ground water is formed by an accumulation of gravitational water at a certain soil depth. This idea was not challenged until Volger (1877) declared that ground water originated by condensation of atmospheric vapor. Still later, Lebedev (1928) combined both theories and suggested that ground water is formed by both infiltration and condensation. From a practical standpoint, it is important that the ground water is noncapillary or free water which accumulates over impervious strata.

The upper limit of the subterranean zone of saturation is known as the **ground water table**, a generally accepted but somewhat misleading term. The ground water does not always exhibit a level surface, but a zigzagging or undulating contour which has a tendency to follow relief; in moderately sloping topography it nearly parallels the land surface.

The ground water is a highly dynamic entity. It possesses a hydrostatic potential and moves in a lateral direction with a speed determined by the porosity of saturated layers and the gradient of the water-bearing strata. Ground water also fluctuates in a vertical direction under the influence of climatic and biotic factors. After heavy rains or melting of snow, the ground water level may rise several feet above its normal position. In a time of drought, evaporation and activity of roots may depress the ground water several feet below its normal state. Therefore, in soil surveys the reference to the ground water level should always be made with regard to the predominant position which the ground water table occupies during most of the year; this position is marked in the soil profile by a deoxidized, discolored, or mottled zone of the gley horizon. Figure 8–13 presents an illustration of the prevalent state of the water table, marked by gleization, and the state of the ground water level observed in open wells at the time of a prolonged drought (Wilde *et al.*, 1953).

The soil above the ground water table exerts a certain tension, whereas the tension of the ground water is zero. Therefore, between the water table and the soil above it, there exists a capillary gradient which is responsible for the upward rise of water. In the opinion of Vageler (1932), the ascent of water from the water table is accomplished by a combined effect of capillary forces, hydration

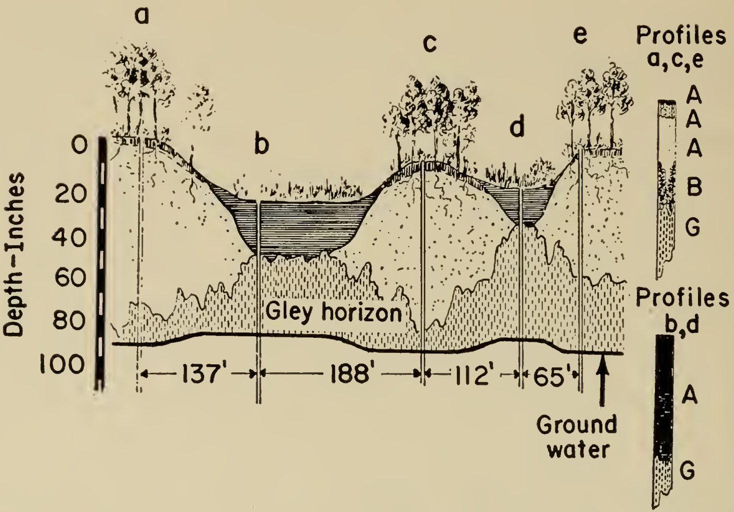


FIG. 8-13. Position of the phreatic water table and of the gley horizon in a sand-peat complex under cover of 30-year-old aspen and under sedges. Observations made at the end of the growing season. (After Wilde *et al.*, 1953.)

energy, and the action of swarm ions. Whatever the cause, the rise produces a moist zone above the ground water table called the **capillary fringe.** In fine-textured soils the capillary fringe may attain a height of several feet; in sandy soils it seldom exceeds 1 foot and is a fraction of an inch in gravelly deposits (Keen, 1931). The partially saturated zone of the capillary fringe possesses sufficient aeration and is penetrated by the active root systems. The survival of trees in time of drought often depends, not on water stored in the upper layers of the soil, but on the relative thickness of the capillary fringe. Trees on sandy and some clay soils with a narrow or sluggish capillary fringe are more exposed to drought than are trees on loam soils with a fringe of 30 to 40 inches.

Depending upon the origin, two principal forms of ground water are recognized: **true** or **phreatic ground water** and **suspended** or **vadose ground water.**

The true ground water forms a sheet over the air-free substratum. This water has considerable stability, for its supply is constantly enriched by infiltration and the subterranean currents which follow the inclined water-bearing strata. Therefore, true ground water usually maintains its capacity to provide water for wells, and consequently it is referred to as **phreatic water** or "well water" (Meinzer, 1923).

The entire portion of soil above the true ground water table, including the capillary fringe, is termed the nonphreatic zone, which is the zone free of well water. As a rule the nonphreatic zone periodically carries percolating water and thus is identical with the **infiltration zone**. In some instances however, infiltrating water is arrested in its downward movement by a combined action of the capillary forces and the roots of vegetation. Under such conditions the nonphreatic zone shows two essentially different layers: the upper, **infiltration zone**, carrying percolating water; the lower, nonpercolated zone of dryness, or the **xero-zone** (Fig. 8–14).

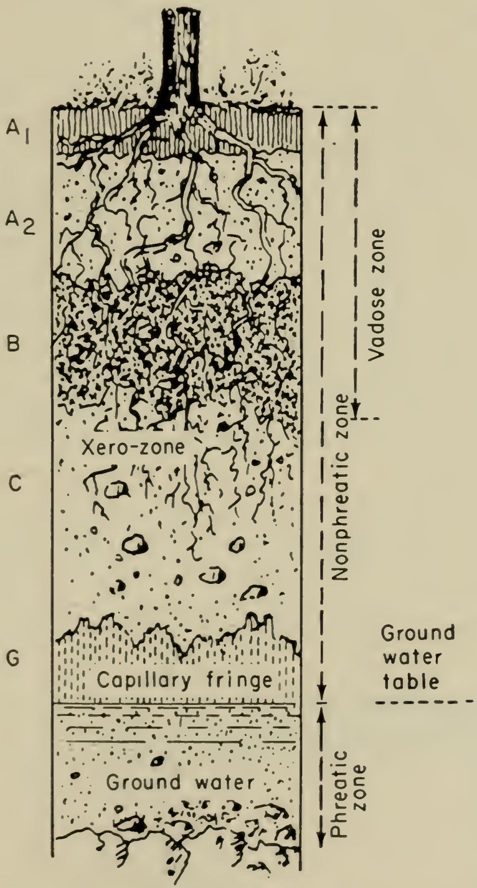


FIG. 8–14. Schematic presentation of important hydro-regions in a leached sandy loam soil. Note the difference in phreatic and vadose water, the extention of the capillary fringe, and the location of the xero-zone which often receives a low supply of infiltration water and is impoverished in moisture by the action of roots.

The low permeability of a certain portion of the soil profile may hinder percolation and thus cause an accumulation of gravitational water above the true water table. Such an accumulation of free water is referred to as **suspended ground water** or **vadose water.** The upper limit of vadose water is known as a **false** or **perched water table.** As a rule the false water table is located within a few feet from the surface. It does not usually provide water for wells and is less stable than the phreatic water table. The influence of the false water table upon the distribution and growth of forest stands may or may not be similar to that of the true water table. The recognition of the two basic forms of ground water—phreatic and vadose—is of utmost importance in dealing with the hydrological relationships of soils and forest vegetation.

The occurrence and depth of the ground water table are closely related to the texture and permeability of the soil. Fine-textured soils retain precipitation in their capillary pores, and a large share of it is returned to the atmosphere by evaporation and transpiration. Sandy soils permit rapid infiltration of rainfall which accumulates over impervious substrata. For these reasons sandy soils have a high water table much more frequently than do fine-textured soils (Filatov, 1945). The formation of a shallow ground water table in coarse sandy deposits of the inter-dunal depressions follows a rather unique pattern. Such depressions accumulate melt waters as well as dust. In time, the latter is incorporated into the soil by infiltrating water and forms a thin impervious water-bearing layer or film of brown color (Glinka, 1931).

The relative stability of the water table depends upon many conditions. Ground water located at a shallow depth is likely to exhibit greater pulsations than that located at a considerable depth, partly because the latter is not exposed to evaporation and activity of root systems. The surrounding topography and the configuration of the water-bearing strata exert a particularly strong influence on the amplitude of ground water fluctuation. On level areas the fluctuation seldom exceeds 1 foot (Koehne, 1933), but in inter-dunal depressions, which collect runoff and seepage water, the melting of snow may produce a rise of the water table exceeding several feet. The transpirational effect of forest stands during the growing season may also cause a drastic lowering of the ground water. This relationship of forest cover and water table is of special importance in forestry work, and its discussion follows.

Influence of forest cover on the water table. The effect of forest cover upon the state of ground water is well illustrated by the

Trappist monks' experiences at the Tre Fontana near Rome. This area once included extensive swamp lands and was known as a dangerous malaria center. In 1868 members of the order established on wet grounds a plantation of eucalyptus, a tree characterized by a deep root system, fast rate of growth, and ability to transpire large quantities of water. As a result, the ground water table was lowered three and a half feet, and the population of malarial mosquitoes was greatly reduced.

A similar influence of forest cover on ground water was later revealed by a number of systematic investigations conducted on plains in different parts of the world (Ototzky, 1897; Henry, 1903; Pearson, 1907). The lowering of the ground water was explained largely as the result of the interceptional and transpirational effects of the forest canopy. Observations in mountain regions and in tropics, however, have suggested that the relationship observed on the plains of temperate regions may be reversed, and ground water may be found closer to the surface under forest stands than in open areas (Ribbentrop, 1900; Engler, 1907; Wissotzky, 1938). This is presumably caused by the greater permeability of forested soils or by the greater evaporation from open areas during hot periods (Zon, 1927).

Even on the plains of the temperate and cold regions the influence of forest cover on the state of ground water is subject to wide variation. According to Ototzky (1906) the differences in the ground water levels between forested land and grassland amounted to 35 feet at the distance of a few hundred feet (Fig. 8–15). His observations were made in loessial deposits of the prairie-forest region of Russia. In the environment of Germany, however, the lowering of the ground water table under spruce stands did not exceed 32 inches (Ebermayer, 1900). In coarse sandy soils of Wisconsin, the

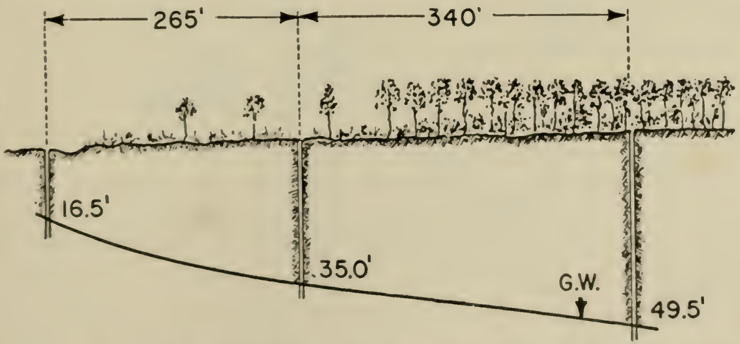


FIG. 8–15. A 34-foot depression of the ground water table by an oak stand on a prairie-forest silt loam derived from loess. Shipov Forest, southern Russia. (After Ototzky, 1905.)

maximum depression of the phreatic ground water table was less than nine inches (Fig. 8–16). A clear cut of mature aspen stand on a podzolized sandy loam soil in the same state raised the vadose ground water 14 inches and thus temporarily converted a reasonably well-drained soil into a semiswamp. This alteration occasionally was accompanied by increased runoff, erosion, and damages to roads (Wilde *et al.*, 1953).

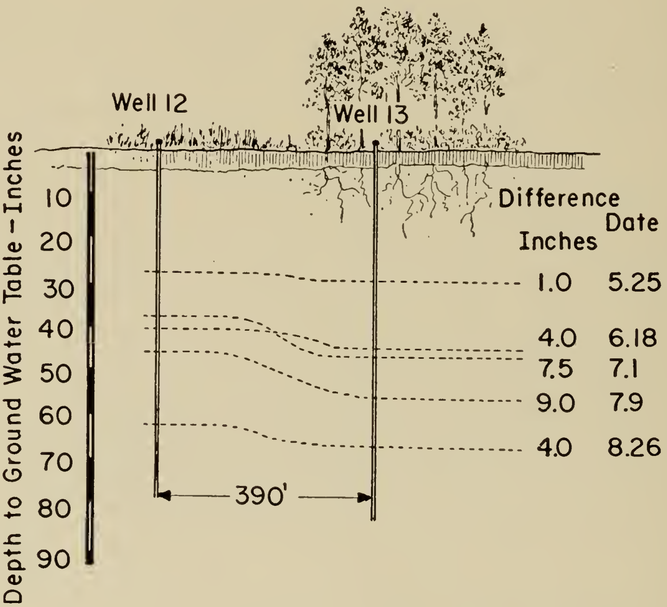


FIG. 8–16. Position of the phreatic water table in a level coarse sandy soil under sod cover and under a 40-year-old oak-jack pine stand. (After Wilde *et al.*, 1953.)

This effect of clear cutting is in agreement with the observations of Lundberg (1926), who stated that in Sweden the forest cover with its transpiration is the best ally of drainage work. For this reason, Lundberg recommended the maintenance of forest cover on drained peat bog, regardless of the quality of timber. Hesselman (1928) also observed that the development of swamps on upland soils is encouraged by clear cutting of the forest. In his opinion this process is amplified by the impregnation of the surface soil with the products of organic matter decomposition. These ideas were substantiated by the observations of Tiurin *et al.* (1935), who reported a considerable increase in the moisture content of the surface layers of soil or the formation of a perched ground water table on deforested lands. In the humid environment of Canada, clear cutting gives rise to the development of moss peat bogs on level areas of lacustrine clays which are perfectly drained under a mature forest cover (Wilde, Voigt, and Pierce, 1954).

Effect of ground water on forest growth. The ground water table delineates the depth of soil accessible to the penetration of roots of many tree species (Büsgen and Münch, 1929; Heyward, 1933; Sukachev, 1932; Woodroof, 1933). A water table located at a shallow depth, therefore, diminishes the supply of nutrients available to the trees, reduces the stability of stands against the wind, and often shortens the growing season. The adverse influence created by the high ground water, however, varies considerably with different tree species. The so-called phreatophilic trees, such as willow, cottonwood, sycamore, gum, white cedar, tamarack, and spruce, can tolerate prolonged inflow of the ground water (Meinzer, 1923). Some phreatophilic trees, namely Norway spruce, bald cypress, and pitch pine, have the ability to penetrate through the waterlogged horizon of the perched water table into the lower, better-aerated layers (Hasselman, 1910; McQuilkin, 1935). Contrariwise, red pine, hard maple, and other phreatophobic species are likely to deteriorate on soils underlain at a shallow depth with ground water, especially if it is not well oxygenated (Tamm, 1950). The ground water table located at a suitable depth, such as four feet, provides an increased supply of moisture and is highly beneficial to tree growth. This is especially true of coarse sandy soils where the ground water is liter-

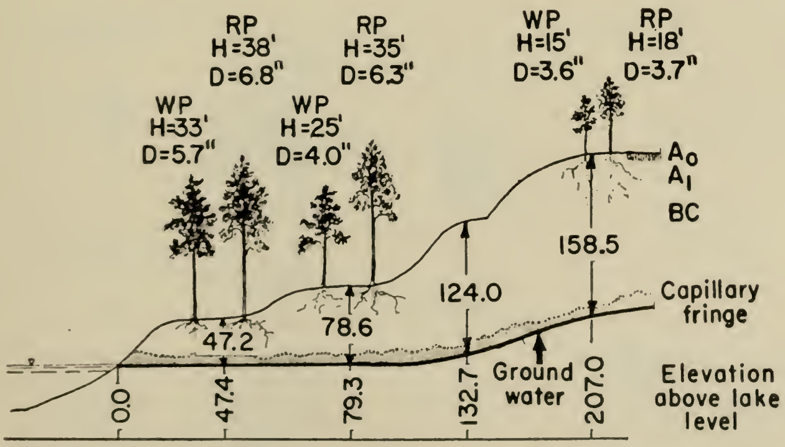


FIG. 8-17. Effect of ground water on the growth of 22-year-old plantation of red and white pine on a coarse sandy soil. Position of ground water during the middle of July. *WP*—white pine; *RP*—red pine; *H*—average height; *D*—average diameter breast height. (After Dosen *et al.*, 1950.)

ally "the life blood of the crop," as strikingly illustrated by observations of Dosen *et al.* (1930). Red and white pine trees on a sandy outwash with the water table at a depth of 47 inches reached an average height of 35 feet at the age of 22 years; trees growing at higher elevations with the water table 158 inches deep attained an average height of only 16 feet at the same age (Fig. 8–17).

The growth effect of ground water is much less pronounced in fine-textured soils because of a large supply of capillary water.

The general relationship between the growth of Norway spruce and the depth to the ground water table in morainic deposits of northern Russia, as reported by Sukachev (1932), is given in Table 8–1.

TABLE 8–1

THE RATE OF GROWTH OF NORWAY SPRUCE IN RELATION TO THE GROUND WATER TABLE (AFTER SUKACHEV, 1932)

Depth to water table (ft.)	Floristic type of forest cover	Site index
5.0–7.0	*Picetum fruticosum*	Very high (I)
2.5–3.0	*Picetum oxalidosum*	High (II)
1.5–2.0	*Picetum equisetosum*	Low (IV)
1 or less	*Picetum caricetum*	Very low (V)

In some instances the position of the ground water table influences not only the rate of forest growth but also the composition of the main forest stand. A conspicuous example of this influence is pre-

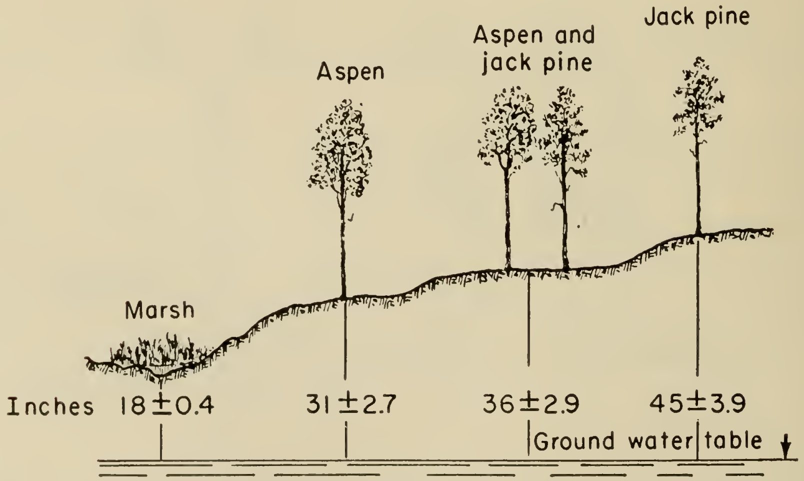


FIG. 8–18. Distribution of jack pine and aspen in relation to the ground water table in Wisconsin. (Wilde and Zicker, 1948.)

sented by the distribution of aspen and jack pine in the region of undulating deposits of siliceous sands (Fig. 8–18). The effect of the ground water table upon the composition and the rate of growth of forest stands in different climatic regions is illustrated in Table 8–2 (White, 1939; Wilde, 1940).

TABLE 8–2

EFFECT OF THE GROUND WATER TABLE ON THE COMPOSITION AND GROWTH OF FOREST VEGETATION IN WISCONSIN (AFTER S. A. WILDE AND D. P. WHITE)

Depth of ground water table (ft.)	Composition of forest stand	Yield at 100 years (cu. ft.)*	Floristic site
A. Podzol Region. Silty-clay loams derived from old granitic drift			
1.0–1.5	Balsam fir, white spruce, black ash and red maple. Understory of mountain ash, tag alder, and willows	2200	Sphagnum-Carex-Equisetum
2.0–3.0	Hard maple, rock elm, red maple, basswood, yellow birch, balsam fir, and white spruce	3500	Fern site
4.0–5.0	Hard maple, basswood, some white pine. Leatherwood and numerous other shrubs	4800	Adiantum-Thalictrum
B. Prairie-Forest Region. Silt loams derived from recent calcareous drift			
0.7–1.2	Lowland meadow	–	Carex site
2.0–3.0	Bur oak, black oak, aspen, and box elder. Abundant hazelnut	1900	Corylus site
4.0–5.0	White oak, red oak, some black oak, walnut, hickory, white ash	3200	Circaea-Amphicarpa-Psedera site

* Yields obtained by interpolation for fully stocked stands.

In German agricultural practice the optimum depth to the ground water table is considered to be 3.5 feet for sandy soils, 5 feet for sandy loam or light loam soils, and 7 feet for heavy loam soils. A deviation from the optimum position of the ground water table entitles the owner of the land to a reduction in taxes (Herzog, 1932).

The beneficial influence of the ground water upon the natural reproduction of forest stands is well known by silviculturists, a relationship which was experimentally demonstrated by Stoeckeler and Sump (1940). However, the abundant natural reproduction on soils influenced by ground water at times leads to crowded stands of undesirable composition. If poorly drained soil is low in nutrients, trees cannot express their dominance and may expend their energy in a hopeless struggle for space. Thus, nature's blessing may turn out to be a forester's curse.

A rapid growth of trees on soils underlain by ground water may also decrease the specific gravity of wood and encourage damages by parasitic fungi, thereby greatly decreasing the value of forest stands (Büsgen and Münch, 1929). The latter adverse effect is especially pronounced on soils of a low fertility.

Aside from the purely physical effect, ground water influences the composition of forest stands, their rate of growth, and their capacity for natural regeneration through its physico-chemical properties. The properties of ground water which have a direct bearing on silvicultural aspects are: reaction, oxidation-reduction potential, content of dissolved oxygen, specific conductance, and total hardness. These properties in their entirety indicate two major conditions of ecological importance: degree of oxygenation or stagnation of ground water, and degree of enrichment of ground water in nutrient elements, particularly bases (Bradfield *et al.*, 1934; Pearsall, 1950; Pierce, 1953).

The least favorable composition of ground water is found in stagnant moss peat bogs or "muskegs." Such water is characterized by a strongly acid reaction of about pH 4; deficiency of oxygen and electrolytes; a very low specific conductance, not exceeding 0.07 millimhos; and a very low negative redox potential. A rapid growth of forest stands often coincides with circumneutral and well-oxygenated ground water which may have as much as 7 ppm. free oxygen (O_2), a specific conductance of about 0.2 mmhos., and a slightly negative or a positive redox potential. Such a composition of the ground water does not decrease appreciably the respiration of tree roots and the activity of soil organisms and precludes the accumulation of organic remains in the form of inert raw humus (Hesselman, 1910). The same conditions are usually responsible for the exceptionally high site index of stands on slopes influenced by a swift seepage. Several investigations have disclosed that the occasional occurrence of rapidly growing forest stands on siliceous sandy soils is due to the fertilizing effect of ground water which was enriched in nutrients through its previous contact with nutrient-bearing rocks, morainic deposits, or lenses of lacustrine clay (Hartmann, 1928; Wilde and Randall, 1949). Ground water high in carbonates may be responsible for a premature deterioration of forest stands; such water is likely to possess a specific conductance exceeding 0.5 mmhos. and hardness between 100 and 300 ppm. In the semiarid regions of grasslands or desert-forest transitions the high content of soluble salts in ground water indicates sites on which afforestation is virtually impossible.

WATER VAPOR AND CONDENSED WATER

A small portion of the total soil moisture is made up of water vapor, for the relative humidity of the soil air does not fall much below 100 per cent until the supply of capillary water is exhausted by drought.

Water vapor moves from higher to lower pressure regions in accordance with the variations in the moisture and temperature of the soil. Such movement may be particularly expected in the winter in response to the temperature gradient (Edlefsen and Bodman, 1941). If the vapor enters a medium of low temperature, the dew point may be reached and the vapor may condense. In the opinion of some investigators, the process of condensation is responsible for a prolonged saturation of soil below the frost line and in turn an accumulation of stable products of anaerobic fermentation (Williams, 1949; Gurr *et al.*, 1952).

The importance of the condensed moisture was strongly emphasized by Sigmond (1912), who advocated the principle of rugged surfaces in handling both the land and the canopy of the forest. At a later date, the subject of water condensation was intensively investigated by Lebedev (1928) who reported that water condensed from the air in a single year was equivalent to a precipitation of 70 mm. The same author pointed out that a cool and dry period, followed by a hot spell, may impoverish the deep layers of soil in moisture through the condensation of water at the surface and its subsequent evaporation. During cool nights of summer, however, young plantations may be benefited by reduced vapor pressure in the surface soil layer and condensation of water vapor from the warmer deep horizons.

SOIL TEMPERATURE

Undisturbed forest cover with its canopy and humus layer protects the soil against scalding temperatures. The removal of trees in clear cut logging or heavy partial cuttings, however, may raise soil temperature to the level lethal to germinating seedlings. A similar relationship exists in regard to low temperatures. The soil freezes to a considerable depth only on deforested areas, especially if snow cover is delayed. This often leads to so-called "winter injury," that is, killing of trees by strong evaporating winds while the frozen soil has no available water. The soils of nursery beds in prolonged hot periods occasionally develop extremely high temperatures dangerous to stock. This can be prevented by shading or artificial irrigation.

The use of thermistors provides a convenient method for recording soil temperatures.

SOIL COLOR

The color often serves as an indicator of several important characteristics of soils: their geologic origin, enrichment in humus, degree of oxidation or reduction, and leaching or accumulation of certain chemical compounds, particularly iron. However, color does not always present a dependable criterion of soil condition that can be accepted without further investigation. More than once the black surface layer of purely siliceous or poorly drained soils led agricultural pioneers to the blind alley of tax delinquency and abandoned farms. The light gray color, common to the impoverished surface layers of podzolized soils, at times conceals an abundant supply of readily available nitrogen found in cryptorganic soils. A red color of similar hue in soils of different texture may be produced by either 2 or 10 per cent of iron oxides (Ramann, 1911).

In too many instances color has served and still serves as the basis for the genetic soil classification (Robinson, 1949, p. 462). It is sufficient to mention that the brown color, the most common shade of the soil profile, was used for the designation of no less than twelve large groups of soils, namely, "brownearth" or "brown forest soils," "brown nonforest soils," "gray-brown podzolic soils," "gray-brown calcareous desert soils," "brown podzolic soils," "subarctic brown soils," "podzolized brownearths," "noncalcic brown soils," "solonized brown soils," "yellowish-brown lateritic soils," "reddish-brown lateritic soils," and "brunigra soils."

Besides the difficulties presented by the "terminological spectrum," the verbal kaleidoscope of modern pedology is complicated by the fact that many "brownearth soils" or "brown soils" are not of brown color, and many brown soils are not brownearths (Wilde, 1953).

Because of the general lack of knowledge about color on the part of soil specialists, the discrepancies encountered in description of soil profiles are astonishing to anyone familiar with artists' interpretation of hue, value, and chroma. These discrepancies were in a large measure removed through the introduction of the Munsell Color Charts (Rice *et al.,* 1941).

The soil is the chemical laboratory in whose bosom various decompositions and synthesis reactions take place in a hidden manner.

—Berzelius

9

Chemical properties of forest soils

Significance of soil chemistry in silviculture. Opinions as to the relative importance of the physical and chemical properties of soil have varied considerably in the course of the past 150 years. In the early days of scientific soil research, interest was concentrated upon the chemical composition of soils, and soil science was synonymous with agrochemistry. Some of the outstanding students of this period, Boussingault, De Saussure, Liebig, Lawes, and Gilbert, established the basic relationships of plant nutrition and revealed the significance of fertilizer salts. Unfortunately, at that time the chemical analyses of soils employed strong hydrochloric acid which extracts much greater quantities of nutrients than are actually available to plants (Hall and Plymen, 1902). For this reason, a correlation between chemical composition of soils and plant growth was seldom observed. This discrepancy led S. W. Johnson to proclaim in the *American Journal of Science* in 1861 that he "would rather trust an old farmer for his judgment of land than the best chemist alive" (Hopkins, 1910). Consequently, the interest in soil chemistry declined, and emphasis was placed on the physical properties of soils, particularly on the behavior of soil colloids, moisture relations of soils, and soil aeration.

With an increase in theoretical knowledge, however, soil science once again focused its attention on soil chemistry. The work on the exchange properties of soils, structure of clay minerals, availability and fixation of nutrients, the role of trace elements, and composition of plant tissues revealed many important relationships between soil and plant growth. In a large measure, this progress in soil chemistry was achieved through the introduction of modern research equipment, such as the potentiometer, resistance bridge, photoelectric cell, X-ray, spectrophotometer, supercentrifuge, electron microscope, chromatograph, and isotope counters. As a result, the sharp division line between soil physics and soil chemistry became obliterated. In fact, most of the phenomena essential in the behavior of plants were recognized as belonging to the realm of physical chemistry.

The newer knowledge of soils, accumulated during the last thirty years, has solved many old problems of forestry and now plays an essential part in the management of nursery soils, tree planting, and silvicultural treatments of forest stands.

SOIL REACTION

Meaning of the pH symbol. Originally it was believed that soil reaction was caused by the relative concentration of hydrogen and hydroxyl ions present in a solution or a soil suspension. Acidity was said to be due to an excess of H ions over OH ions and alkalinity to an excess of OH ions over H ions; a neutral reaction was presumably produced by an equal number or concentration of H and OH ions. Based on this assumption, Sörensen (1909) introduced the pH symbol, which is the logarithm of the reciprocal of the H-ion concentration. If the H-ion concentration of a solution is $\frac{1}{1000}$ gram per liter, the logarithm of the reciprocal is 3, and hence the pH of this solution is 3. Obviously, the smaller the pH value, the greater is the H-ion concentration, or the acidity. Because the product of the ion concentration of pure water at 24° C.—or the ionization constant—is 10^{-14}, the concentration of either H or OH ions is equal to 10^{-7}. Therefore, the pH value of pure water or a neutral solution is 7. In alkaline solutions, the OH-ion concentration exceeds that of the H-ion concentration, and the pH value is greater than 7. On this basis, soils of pH 6, 5, and 4 should contain a concentration of H ions equal to the concentration of OH ions found in soils of pH 8, 9, and 10, respectively.

The pH scale was devised in the belief that strong electrolytes are only partly dissociated in dilute solutions. This idea proved to be erroneous, and hence the Sörensen pH scale is not scientifically correct (Moore, 1950). Actually, the pH value expresses the **activity** rather than the concentration of hydrogen or hydroxyl ions. Therefore, we must accept today that pH is simply a number read on a potentiometer, preferably that employing a glass electrode.

Empirical as it may be, the pH value exerts a definite influence upon the life functions of organisms, availability of nutrients, and physical properties of soils. This value can serve as a useful tool in the management of soils for the production of farm and forest crops. However, the concept of pH must be freed from the various misapprehensions which have been attached to it in the past (Wilde, 1954).

The pH value of soils and the growth of plants. The literature of today presents the optimum ranges of the pH values of soils for numerous cultivated and autochthonous plants. Such data give, at best, a very crude approximation of reality, for the effect of soil reaction is often drastically modified by the climatic conditions of the area, content of soil colloids, supply of nutrients, and other conditions. Recent observations have removed several unqualified generalizations pertinent to the effect of soil reaction on the distribution of forest vegetation.

White oak, tulip poplar, beech, sycamore, and other exacting hardwoods of North America show at times an exceptionally high rate of growth on fine-textured soils with a reaction as low as pH 4.6 (Wilde, 1950). The suggested optimum pH ranges for tulip poplar and sycamore are 6.0 to 7.0 and 6.0 to 7.5, respectively (Spurway, 1941). According to findings of Åslander (1952), the distribution of Norway spruce, European birch, oak, basswood, and beech is influenced by the nutrient content far more than by the pH value of soils. In the continental climate of the Great Lakes region of the United States, black spruce is confined to strongly acid soils; in the humid environment of Canada, the same species thrives on calcareous deposits and peat soils underlain by alkaline ground water (Pierce, 1953). Hemlock and balsam fir are at the top of the list of acid-preferring or acid-tolerant species; nevertheless, Galloway (1940) observed that these trees grow successfully on calcareous soils of pH 7.3 to pH 8.0.

What is said about trees is equally true of lesser vegetation. Under certain conditions, plants which are rated as "acidophilous," such as *Rumex acetosella*, *Ledum groenlandicum*, and *Chamaedaphne calyculata*, thrive on soils of alkaline reaction and even on outcrops of limestone. *Ledum groenlandicum*, whose optimum reaction range was believed to be between pH 3.0 and pH 5.0, attains in a humid climate luxuriant development on calcareous substrata with a reaction approaching pH 8.0.

In broad terms, the relation between the pH value of soils and the distribution of plants is expressed by an equation whose important coefficients include the length of the growing season and the supply of total moisture available to plants. The longer the season, the higher is the tolerance of plants toward soil acidity; the higher the humidity, the more beneficial is soil alkalinity. Thus, the early classification of vegetation by Unger (1836) into "lime-loving," "lime-tolerant," and "lime-avoiding" plants holds true only within restricted geographic localities.

Serious misconceptions are also encountered in regard to the direct influence of hydrogen and hydroxyl ions on the growth of plants in soils and in nutrient solutions.

The observations of the effect of different acids and alkalies in artificially prepared cultures suggested that free H^+ or OH^- ions are toxic to plant roots even when present in minute concentrations. Today this assumption is largely disproved by experiences in both farming and silviculture. The work of Arnon and Johnson (1942) has shown that plants may be directly injured only by solutions of extreme acidity or alkalinity exceeding pH 3 and pH 9. Experience with forest tree seedlings provides many illustrations of the fact that the toxicity of hydrogen ions has been grossly exaggerated. As found by Olson (1944), healthy pine and spruce seedlings are raised in hydroponics at a double or triple rate of normal growth at a reaction of pH 4.0, and in some cases even lower (Fig. 9–1). In

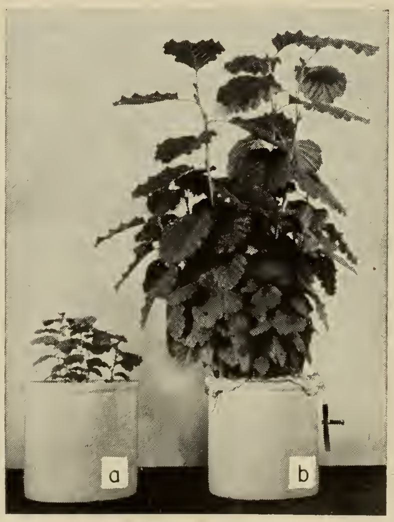


Fig. 9–1. Normal development of European alder, *Alnus glutinosa,* in a fertile nursery soil (*a*) and phenomenal growth of the same tree in a hydroponic culture of an extremely acid reaction approaching pH 4.0 (*b*). The plants are 10 weeks old. (After G. W. Wallis, 1957.)

order to control damping-off disease, nurserymen saturate the seed-bearing layer of soil with a 2 per cent sulfuric acid solution (Wilde, 1937), thereby raising the concentration of hydrogen ions in the soil solution to nearly 0.01 g. per liter. Yet this drastic treatment does not preclude germination of the seed and the normal development of the seedlings, provided that they receive an adequate supply of nutrients from the lower untreated portion of the soil or from the applied liquid fertilizers.

Within certain limits, hydroxyl ions behave in a way similar to hydrogen ions. The low productivity of many alkaline soils is due to the deficiency of nutrients, rather than to an injurious effect of hydroxyl ions (Truog, 1948). Strong alkalinity of soil, exceeding pH 8.0, however, is associated with the presence of sodium carbonate and other toxic compounds and is much more detrimental to most tree species than soil acidity.

One of the cardinal shortcomings of the pH value is that it does not express the total acidity or total alkalinity of the soil or the soil's capacity to neutralize acids and alkalies. Besides the base-forming and acid-forming constituents, the neutralizing capacity of a soil depends upon the content of buffering substances, such as humus and clay. At times the total acidity or alkalinity of the soil is of a much greater ecological importance than the mere pH value. Siliceous sands with a sprinkling of calcareous dust and slightly weathered limestone outcrops analyzing 70 per cent of $CaCO_3$ equivalent have the same reaction of pH 8.0. Sandy soils of this reaction, however, support healthy and rapidly growing plantations of Scotch pine and other lime-intolerant species, whereas highly calcareous soils may induce chlorosis or root rot even in pronounced basophilous hardwoods. Therefore, analysis of alkaline soils must often include the determination of free carbonates.

All of the outlined limitations of the pH concept must be considered for a correct appraisal of the influence of soil reaction on the growth of nursery stock, selection of planting sites, and technique of silvicultural cuttings.

Reaction of nursery soils. In no other plant culture does the supply and ratio of nutrients play such a decisive part as in nursery beds crowded with tree seedlings. At a high degree of acidity, below pH 4.7, tree seedlings may suffer from the low availability of nitrogen, phosphorus, potassium, and other bases. This is particularly true of exacting deciduous species. An alkaline reaction above pH 8.0 may also decrease the availability of phosphates, iron, boron, zinc, and manganese. It may promote a too-vigorous development of microorganisms competing with seedlings for nutrients. As has been shown by previous studies, the harmful influence of lime applied to nursery soils is not a result of the increased reaction but of the stimulated microbiological activity and consumption of available nitrogen by saprophytic bacteria (Wilde, 1946).

Another important aspect of the reaction of nursery soils is its effect on parasitic fungi which attack the roots of seedlings and transplants, particularly those of coniferous species. As a general rule, the virulence of these organisms increases in direct relation with the pH value and attains its peak in alkaline soils (Fig. 9–2).

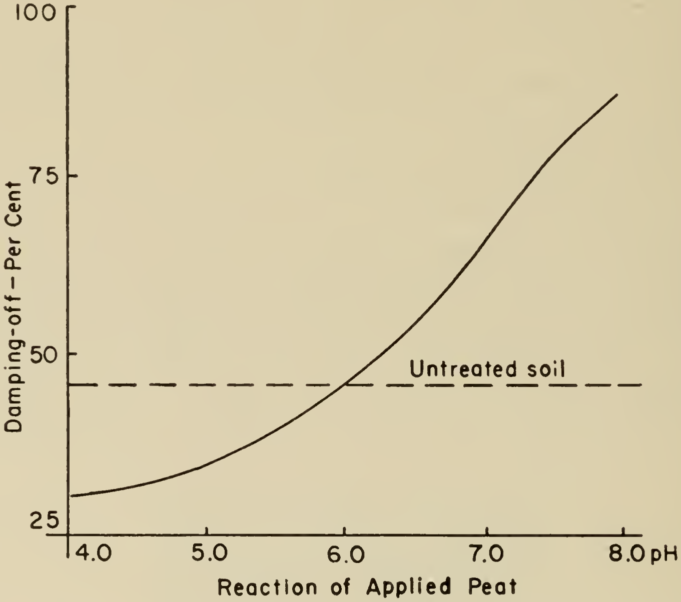


FIG. 9–2. Relation between the severity of damping-off disease of red pine seedlings and the application of peat of different pH values applied at the rate of 80 cubic yards per acre. The curve is based on interpolated results. (From Wilde and Hull, 1937.)

Considering both the nutritional and biological aspects, the desirable reaction range of nursery soils for most coniferous species lies between pH 5.0 and 5.5 and that for most deciduous species, between 5.7 and 6.5. The technique of the reaction adjustment is outlined in the section concerned with the maintenance of fertility of nursery soils.

Soil reaction and tree planting. Only general suggestions can be made in regard to the effect of soil reaction on the growth of planted trees because the significance of the pH value of soils varies greatly under different climatic conditions as well as in soils of different colloidal content.

It is safe to state that a reaction between pH 5.0 and pH 7.0 has little influence on the choice of trees to be planted. A reaction below pH 5.0, however, deserves attention because strong acidity is indicative of severely leached soils of poor physical condition; such soils are often underlain by cemented or compacted accumulative layers which restrict the choice of species and require special methods of tree planting. Alkaline reaction serves as a warning that the soil may be unfavorable to tree growth because of a high content of carbonates or a high concentration of soluble salts.

The soil is not homogeneous in its pH value (Truog, 1918), and trees may escape the unfavorable influence of an extreme reaction by feeding on the less acid or less alkaline portions of the soil. This is especially true of trees produced by direct seeding; their roots after germination grow gradually into the soil and avoid regions of toxic H- or OH-ion concentration. In planting, however, the roots of seedlings are subjected to any existing extremes of reaction. For this reason, the natural occurrence of a tree species on a soil of a certain average reaction is not always proof of the suitability of this soil for planting with the same species.

The approximate optimum pH ranges of different trees are given in Chapter 15, Soils and Reforestation.

Soil reaction and silvicultural cuttings. The significance of soil reaction in thinnings and selection cuttings has been generally overlooked in both forestry writings and practice. In part, this is because the effect of soil reaction in this phase of silviculture is usually obscured by more influential ecological factors. Yet, in many instances, the knowledge of the pH value or the neutralizing capacity of the soil helps to choose the appropriate technique of silvicultural cuttings.

The occurrence of the ground cover vegetation on soils of strongly acid reaction is usually restricted to "raw humus" plants which do not show rank growth on exposure to light and hence permit opening of the stand by comparatively heavy cuttings. Frequently, such cuttings are required to intensify the activity of microorganisms and the decomposition of acid raw humus. A strongly acid reaction of soil occasionally indicates the presence of an impervious hardpan or claypan horizon and may safeguard against the use of cutting methods which decrease the stability of the stand.

Soils of circumneutral reaction are predisposed to an invasion of shrubs and herbaceous vegetation whose competition with natural reproduction must be controlled by very conservative cuttings (Fig. 9–3). A high pH value favors the incidence of damping-off disease and may present a serious obstacle to natural regeneration of certain species, particularly artificially established conifers. This condition appears to be especially serious in coniferous plantations outside of their native regions.

The reaction of a soil is often closely correlated with the rate of decomposition of organic remains and has a bearing upon the fire hazard and the method of slash disposal.

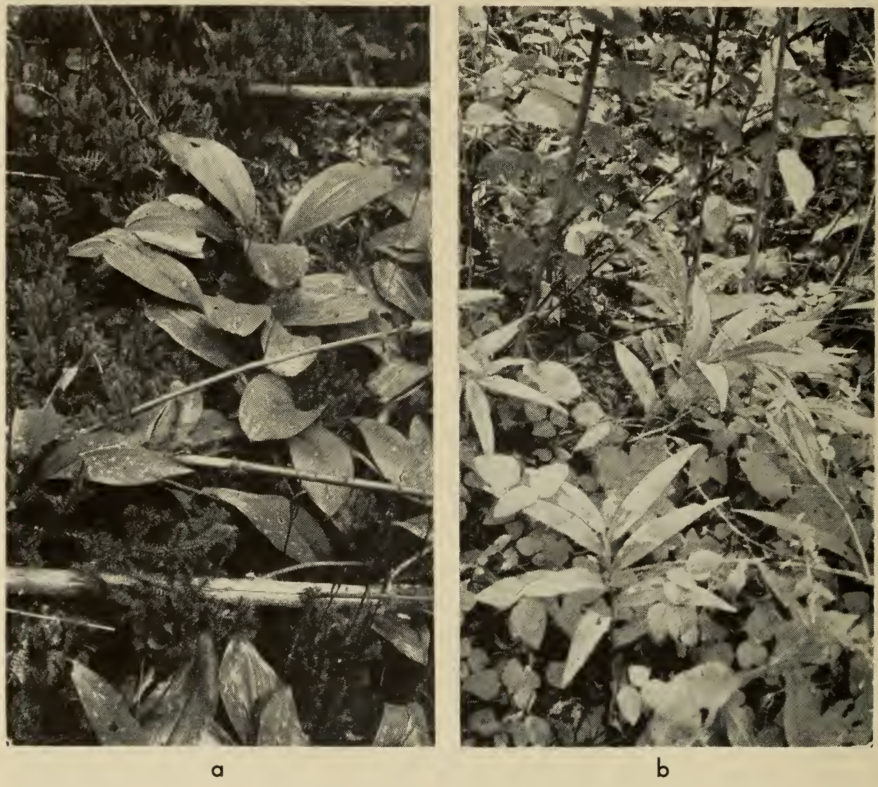


FIG. 9–3. Ground cover vegetation in hemlock-hardwood stands on morainic loams of different reactions. (*a*) Shrub-free ground cover association on strongly acid soils of average pH 4.5, including blue bead, club mosses, and other raw humus plants which are totally incapable of competition with natural forest reproduction. (*b*) Association of plants on slightly acid soils of average pH 6.0, including different members of the lily family, other mesophytes, and many shrubs which could easily suppress natural reproduction upon opening of the canopy.

PLANT NUTRIENTS: THEIR INFLUENCE UPON THE GROWTH OF TREES

Early students of the plant environment were inclined to overemphasize the role of water in plant growth and paid little attention to nutrients. The noted text on plant ecology by Warming (1895) is a striking illustration of this tendency. The original Danish edition of this book exclusively considered the soil moisture. Only after this work had been revised by Graebner did the influence of soil nutrients receive deserved attention.

The underestimation of the importance of plant nutrients was particularly marked in regard to tree growth. This attitude is not without foundation, because trees growing at a wide spacing utilize nutrients from an enormous volume of soil and increase the nutrient content of the surface soil layers through annual leaf fall (Fig. 9–4).

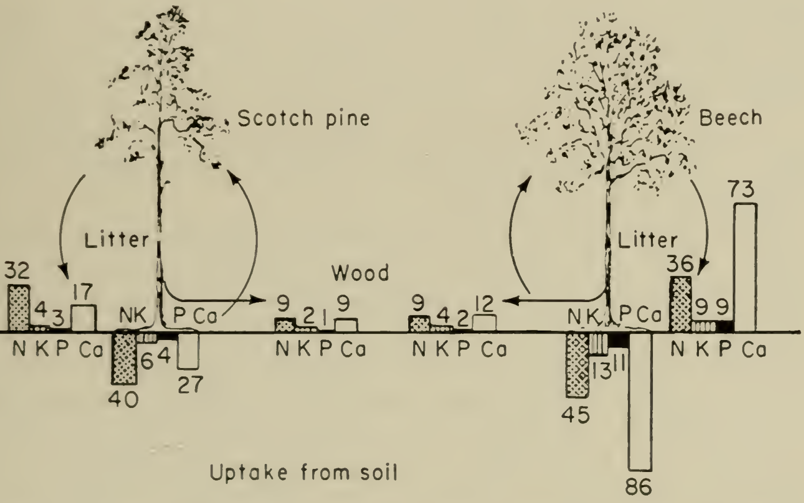


FIG. 9–4. Annual uptake, retention, and return of essential nutrient elements (in pounds per acre) by Scotch pine and European beech. Note the large fraction of nutrients returned to the soil in the form of forest litter—the rotating capital of forest soil fertility. (After A. Dengler, 1930.)

As stated by Duggar (1912), "Of all object lessons in permanent occupation by plants, that of the aged forest stands out supreme . . . So far as may be seen, or measured by the short space of agricultural record, there is with the greater growth of the forest an ever increasing fertility of the land." This beneficial effect of forest cover, however, is often reversed by clear cuts, fires, erosion, grazing, cultivation, and forester's misplacement of tree species, all of which may create nutrient deficiencies in forest soils.

If seeds of trees are planted in quartz sand or in soil of inadequate fertility, the growth of seedlings is arrested as soon as the supply of nutrients stored in the seed is exhausted (Mitchell, 1939). Species that have small seeds, such as spruce and elm, react immediately to a deficiency of soil nutrients. Species that have a large supply of plant food in the cotyledons, such as oaks and walnuts, show a rapid early growth regardless of soil fertility. Seedlings may survive on poor soils for a considerable number of years, producing little or no top growth but concentrating all available energy upon the extension of the roots. As Liebig expressed it, "The roots search for the nutrients as though they had eyes. . . ." If the starving seedlings obtain nutrients at a greater soil depth, they may recover and gradually attain a satisfactory development. Very often, however, the period of malnutrition is terminated by parasites or adverse environmental factors. Examples of a critical shortage of nutrients are presented by struggling stands or plantations of black locust, spruce, oak, and other exacting species growing on infertile soils, including those with an adequate supply of water. A deterioration of tree seedlings due to a lack of nutrients is well known to foresters who have had experience with permanent nurseries. A comprehensive report on the uptake of nutrients by mature forest stands was recently made by Rennie (1955).

Of the many elements found in plant tissues, only fifteen or so are indispensable for the growth of trees. According to the somewhat outmoded findings of Sachs and Knop, ten elements were recognized as essential for plant development: carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorus, potassium, calcium, magnesium, and iron. The memorizing of these **major elements** is facilitated, as suggested by Cyril Hopkins, by writing their symbols in the following order—C HOPK(I)NS CaFe Mg—and remembering that this is an abbreviated form of the expression, "See Hopkins Cafe—mighty good." In recent years it has been revealed that the so-called **minor elements** are also necessary for the plant growth. Among these, boron, manganese, zinc, copper, and molybdenum appear to be of primary significance for the growth of trees.

Plants obtain carbon, oxygen, and hydrogen from water and air. Bases, phosphorus, sulfur, and trace elements are supplied by the soil. As a rule, nitrogen is also derived from the soil, but legumes and some physiologically related plants receive part of this element from the air through the activity of symbiotic microorganisms, largely bacteria.

Nutrients fulfill numerous physiological functions in the development of plants. They contribute to the material from which the protoplasm and cell walls are constructed; they influence the hydration of cell colloids, permeability of membranes, and osmotic pressure of plant cells; they provide the cell sap with buffering substances, regulate its reaction, counteract the effect of toxic ions, and act as catalysts or coenzymes. Each element fulfills in plant metabolism one or more specific tasks.

Functions of essential nutrient elements. Although it is common to divide essential nutrients into "major" and "minor," or "primary" and "trace" elements, such a subdivision is arbitrary; in many instances the consumption by trees of so-called "major" elements is below that of the "minor" elements. Moreover, the presence of all essential elements in available form and adequate amounts is equally important to the growth of trees.

Nitrogen is an essential constituent of proteins, which are at the core of all life processes. The large protein molecules of immensely complex structure possess the inherent ability of reproducing themselves. Depending on conditions, this attribute is responsible for the birth and growth of healthy organisms as well as the development of malignant tumors.

In farming, nitrogen is called "the balance wheel of plant nutrition." A deficiency of soil nitrogen is manifested by stunted growth of plants, pale green, yellowish, or reddish color of foliage, premature death of leaves and buds, and underdeveloped root systems. The addition of a nitrogen fertilizer almost immediately intensifies the green hue of the foliage and is followed by an accelerated growth (Fig. 9–5). An excess of nitrogen produces abnormally large, succulent crowns and stems of the plants. The resulting thinning of the cell walls and the reduction of sclerenchymatic tissues decreases the resistance of plants to drought, frost, and parasites.

Nitrogen-bearing organic substances in the soil undergo profound changes induced by microorganisms. The protein-like com-

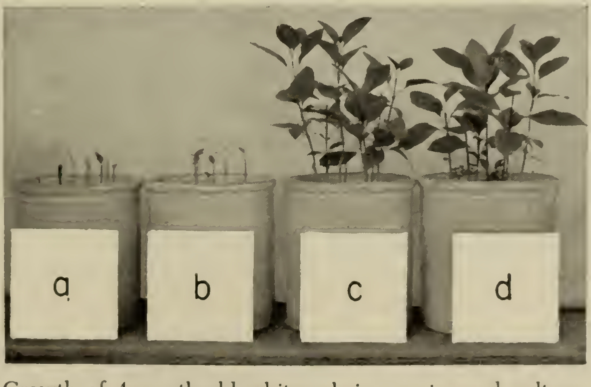


FIG. 9–5. Growth of 4-month-old white ash in quartz sand cultures as influenced by the level of available nitrogen: (*a* and *b*) nitrogen-free nutrient solution; (*c* and *d*) nutrient solution supplied with ammonium nitrate equivalent to 200 pounds per acre.

pounds are broken down into their building blocks, amino acids, and then are converted to ammonia and nitrates. The latter two forms are the most important sources of the readily available nitrogen. The majority of forest trees, especially tolerant conifers such as spruce, fir, and hemlock, have the ability to utilize the nitrogen of ammonia, and perhaps some of amino acids. White ash, tulip poplar, walnut, and other exacting hardwoods feed preferably on nitrogen in the nitrate form (Leiningen, 1925). Under conditions of artificial fertilization, such as are found in nurseries, plants growing in acid soils show better response to nitrate fertilizers, whereas plants growing in alkaline soils give preference to ammonium salts (Prianishnikov, 1951).

The content of total nitrogen in the surface 6-inch layer of virgin forest soils varies from about 0.1 to 0.3 per cent. The content of nitrates (NO_3) seldom exceeds 25 ppm. because of their high solubility, reduction, removal by leaching, and consumption by plants. The content of ammonium (NH_4) may reach 70 ppm. in the humus layers of forest soils, for some ammonium ions are held by mineral and organic colloids.

The determination of the total nitrogen by the Kjeldahl procedure (AOAC, 1950) is one of the oldest and most reliable soil analyses. It is, however, somewhat laborious and is often replaced by the more rapid determination of organic matter. The percentage of organic matter, multiplied by 0.025 or some other conversion factor, gives the approximate content of the total soil nitrogen. Because the carbon-nitrogen ratio varies considerably in different soils, the conversion factor must be established on the basis of local experience.

The contents of nitrate and ammonia nitrogen may be determined colorimetrically by the phenoldisulphonic acid method and Nesslerization, respectively. However, the instability of these compounds in soils justifies their determination only in soils which are suspected to have inhibited microbiological activity. In silvicultural practice, the content of available nitrogen is usually roughly estimated by assuming that in a well-aerated and biologically active soil the annual release of nitrate and ammonia nitrogen amounts to about 1 per cent of the total nitrogen. A content of total nitrogen of 0.2 per cent is adequate for most tree species, and the annual consumption of available nitrogen by trees, shrubs, and ground-cover plants rarely exceeds 40 pounds per acre.

Phosphorus is a constituent of the nucleus and plays an important part in cell division and the development of meristematic tissues. It acts as a catalyst in respiration reactions. The oxidation of phosphorylated compounds aids in the transformation of carbohydrates.

A high concentration of phosphorus is found in the seed even when the seed is produced by trees growing on extremely infertile soils, for the production of seed is regulated by the content of stored phosphorus (Youngberg, 1951). This is a provision of nature which ensures normal nutrition of seedlings in their initial stages of development.

In spite of the important growth functions of phosphorus, its deficiency seldom is strikingly manifested in trees. Only critical deficiency of phosphorus is revealed by a degeneration of lateral buds, restricted branching, and bronzing of foliage. Narrow petiole angles, purpling of the veins at the lower leaf surface, and poorly developed root systems with coarse brown rootlets are other, less conspicuous symptoms.

The correction of phosphate deficiency stimulates the assimilation of carbon dioxide, the utilization of other nutrients, particularly nitrogen, and encourages the development of lateral and fibrous roots (Fig. 9-6). The latter effect of phosphorus is of special significance in northern forest nurseries located on clay soils. On such sites the roots tend to be underdeveloped and the seedlings suffer from winter kill and frost heaving. Studies employing radioactive isotopes showed that phosphorus has a high mobility in plant tissues, being translocated according to the needs from the leaves into growing regions.

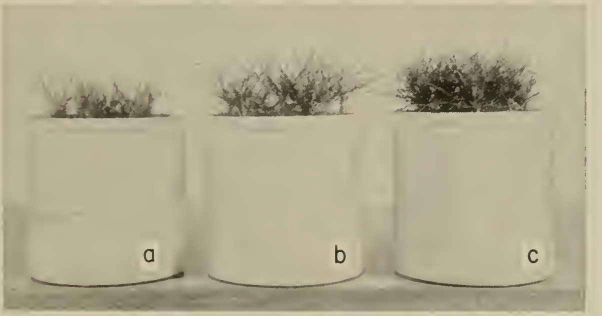


FIG. 9-6. Effect of phosphorus on the development of 2-year-old red pine seedlings: (*a*) untreated nursery soil; (*b*) similar soil treated with rock phosphate at the rate of 600 pounds per acre; (*c*) similar soil treated with 20 per cent superphosphate at the rate of 300 pounds per acre.

Trees derive their phosphorus chiefly from calcium phosphate and organic phosphorus compounds, and to a lesser extent from iron and aluminum phosphates. The content of easily soluble or available phosphorus pentoxide (P_2O_5) varies in virgin forest soils from 10 to 200 ppm. Light-demanding pines and some deciduous pioneer species require only low contents of available P_2O_5, such as 10 or 15 ppm. A content of available P_2O_5 of 50 ppm. is sufficient for most forest trees.

Available phosphorus is determined colorimetrically by extraction with a dilute acid solution and subsequent treatment of the filtrate with ammonium molybdate (Truog, 1930).

Potassium speeds up the assimilation of carbon dioxide and is important in the transformation of carbohydrates, synthesis of proteins, and cell division. It remains in the plant as soluble salt and its function is largely regulatory or catalytic. Potassium is concentrated in the young leaves, buds, and root tips.

A deficiency of potassium hinders the growth of roots and inhibits the normal development of foliage. In time, the leaves may become

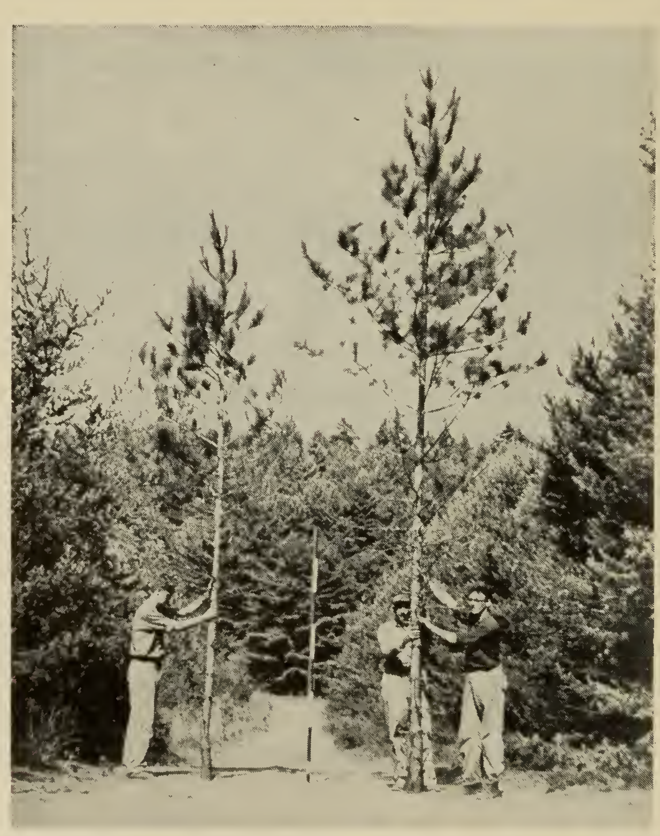


FIG. 9-7. Growth increase of red pine in 25-year-old plantation after a single application of potash broadcast 14 growing seasons before (200 pounds per acre KCl broadcast between rows). Mean sample of trees from $\frac{1}{10}$-acre plots. White bands indicate height at time of treatment. (Plots described by Heiberg and White, 1951, Photo by Will Ulmer.)

bronzed and scorched; they age prematurely and die at the tips or along the edges. The addition of potassium fertilizers increases both the growth and vigor of trees (Fig. 9–7). Potassium counteracts the harmful effect of excessive nitrogen and appears to be instrumental in reducing root rot of older seedlings. It plays an important part in the process of frost hardening of trees, a conversion of starch to sugar at the end of the growing season. This effect is especially important in production of nursery stock (Wohack, 1930; Kopitke, 1941).

Soils ordinarily contain from 1 to 2 per cent of potassium, most of which is provided by feldspars and micas. The content of available potash (K_2O) in virgin forest soils commonly varies from 50 to 200 ppm. The pines are satisfied with small amounts of available potash, such as 30 ppm.; the exacting trees, such as black walnut, white ash, basswood, bald cypress, and Norway spruce, require a content of about 150 ppm.

The determination of available potassium is usually made by extraction of soil with a normal solution of ammonium acetate (Volk and Truog, 1934). However, it has been demonstrated that trees with the help of mycorrhizal fungi may absorb potassium from unweathered feldspar and other potassium-bearing minerals (Fig. 9–8). Consequently, the determination of available potassium in forest soils requires the use of much stronger extracting solutions than employed in agricultural analyses. At the present state of knowledge, the use of boiling 1*N*. nitric acid appears to provide the most satis-

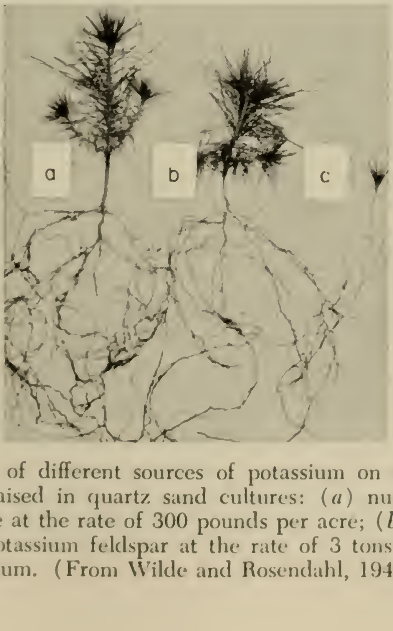


FIG. 9–8. Influence of different sources of potassium on the growth of year-old white pine seedlings raised in quartz sand cultures: (*a*) nutrient solution supplied with potassium chloride at the rate of 300 pounds per acre; (*b*) nutrient solution and 40-mesh to 60-mesh potassium feldspar at the rate of 3 tons per acre; (*c*) nutrient solution without potassium. (From Wilde and Rosendahl, 1945.)

factory information on the content of available potassium in forest soils (Leaf, 1957).

Calcium influences the growth of forest trees directly as a plant nutrient and indirectly by affecting soil reaction and other soil properties. It is particularly important in the development of roots and root hairs. Calcium pectate serves as the cementing material between cells like mortar between bricks, and plants deficient in calcium are characterized by weakness of tissue. Calcium aids in absorption of water and nutrients by favoring adequate permeability of the cell walls. It neutralizes toxic by-products formed in growth processes. A large portion of the calcium of plants is located in the leaves, especially in those of hardwood species (Němec, 1948).

In soils calcium tends to overcome the injurious effects of excessive amounts of sodium, potassium, magnesium, aluminum, manganese, and other constituents which may become toxic to the plants. Development of soil microorganisms depends greatly on the supply of calcium. The formation of either raw humus or mull humus is often associated with the calcium content of soils.

A deficiency of calcium brings about stunted growth and discoloration of the roots. It may also cause a brown spotting of leaves. Under natural conditions, a critical deficiency of calcium is of rare occurrence in forest soils.

Calcium is abundant in limestones, ferromagnesian rocks, and many minerals. The amount of exchangeable or available calcium varies in forest soils from 200 to several thousand parts per million. Even calciphilous forest trees are satisfied with rather moderate amounts of available calcium, such as 1000 ppm., or 5 m.e. per 100 g. (Stone, 1940). Under greenhouse conditions, 800 pounds of calcium per acre was found sufficient to satisfy the requirements of hardwood seedlings (Fig. 9–9).

The determination of available calcium is made by leaching the soil with a neutral salt solution, such as 1*N*. ammonium acetate, and precipitating calcium as the oxalate (Chapman and Kelley, 1930), or using the flame photometer.

Magnesium is the only mineral constituent of the chlorophyll molecule. It promotes the utilization of phosphorus and occurs most abundantly at the growing tips. Magnesium ions appear to be specific activators for a number of enzymatic reactions. Magnesium starvation causes premature defoliation, preceded by chlorosis. In contrast to calcium deficiency, magnesium starvation does not affect the roots until later in the life of the plant. Magnesium salts in excess produce harmful effects which may be lessened by the addition of

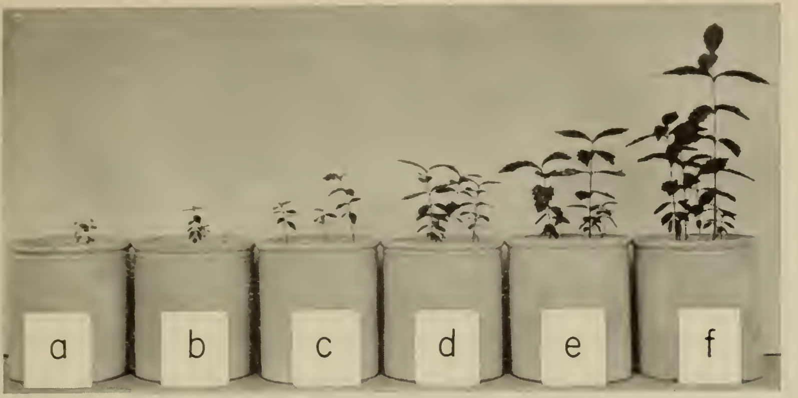


FIG. 9–9. Effect of calcium on the growth of 4-month-old American elm seedlings raised in quartz sand cultures buffered with permutite: (*a*) check; (*b*) 50 pounds per acre of calcium in the form of calcium carbonate; (*c*) 100 pounds per acre; (*d*) 200 pounds per acre; (*e*) 400 pounds per acre; (*f*) 800 pounds per acre. (After E. L. Stone, 1940.)

calcium salts. A critical deficiency of magnesium is encountered frequently in acid-treated soils of forest nurseries and in soils depleted by cultivation, especially those treated with paper mill sludge.

The content of available magnesium in forest soils is usually from one-fifth to one-third that of calcium (Wilde, 1938; Wilde and Patzer, 1940), but a satisfactory growth of trees was observed in greenhouse cultures and native soils at an enormously wide Ca/Mg ratio, exceeding 30. Available magnesium is determined by precipitation from the calcium filtrate by addition of ammonium phosphate (Chapman and Kelley, 1930), or by the use of the flame photometer.

Iron is essential in the formation of chlorophyll, and its deficiency is manifested by the yellowing of leaves or "chlorosis." It is widely distributed in nature and is readily reduced in the presence of oxidizable organic matter. It serves as an oxygen carrier, and its function as an electron donor and acceptor has been compared to the hairspring of a watch.

A deficiency of iron occurs only in circumneutral and alkaline soils depleted in organic matter (Kliman, 1937). It is corrected by application of soluble iron salts to the soil, spraying of the foliage, or injection of iron citrate or iron tartarate into the trunks of the trees (Thomas and Haas, 1928; Bahrt and Hughes, 1937).

Sulfur is a constituent of proteins and plays an important part in the respiration of plants. It appears to favor the development of roots, as well as root nodules. Although soils receive through annual precipitation 3 or more pounds of sulfur per acre, this element may be deficient because of its loss in drainage. According to several reports the addition of sulfur increased the growth of forest seedlings in nurseries. The symptoms of sulfur deficiency are similar to those of nitrogen deficiency.

Minor nutrient elements. Information pertinent to the effect of boron, zinc, manganese, copper, and other trace elements on trees has accumulated largely in work with orchard soils. Most trace elements appear to act as catalysts stimulating the synthesis of chlorophyll and carbohydrates. They exert a beneficial influence upon plants when present in the soil in minute or moderate quantities; at higher concentrations they are extremely toxic.

A deficiency of boron depresses the growth of trees and leads to distortion of leaves, degeneration of terminal growing points, brittleness of stems, and discoloration of roots. A critically low content of boron, less than 2 or 3 pounds per acre, is usually confined to calcareous soils, sandy soils, or soils depleted by farming. An excess of this element causes a browning of leaves and premature leaf fall. A deficiency of zinc is identified with so-called "deficiency diseases" of orchard trees, such as "pecan rosette." Spraying of leaves and treatment of soil with zinc sulfate in many instances corrected a pathological condition of apple, pear, cherry, plum, and citrus trees. A deficiency of manganese effects premature leaf fall and degeneration of growing shoots, particularly common in citrus plants. A form of chlorosis characterized by yellow areas located away from the veins has been noted in a number of tree species due to manganese deficiency in soils with a high content of calcium carbonate. Chlorotic condition of deciduous fruit trees has been traced also to a deficiency of copper. Applications of copper sulfate to the soil or directly to the leaves have corrected the "die-back" of citrus trees and improved the growth of walnuts affected with "yellows" (C.N.E.B., 1948). Pronounced deficiency of molybdenum was also noted in some forest soils.

Information on trace elements in forest soils is far from complete, but according to recent findings of Viro (1955) the deficiency of these nutrients is responsible for retarded growth of trees in many soils.

Availability and balance of nutrients. Nutrients which are incorporated in unweathered minerals and raw organic remains represent the principal capital of soil fertility. From these, plants receive a periodic income of available nutrients in the form of dissolved salts and exchangeable ions, released gradually through the action of biological and chemical agents. The size of this constantly flowing interest can be estimated by leaching the soil with solutions approaching in their effect the extracting capacity of roots. In some instances the available fraction constitutes only 1 per cent of the total supply of the element (nitrogen, potassium); in other cases it may be as great as 10 per cent (phosphorus, calcium).

The fraction of nutrients available to plants is not limited to cations and anions present in soil water, as was believed by some investigators. If the soil solution is not sufficiently supplied with a certain nutrient element, plants may feed directly on mineral or organic soil particles. This **solid phase feeding** is facilitated by the close contact of the growing root hairs or mycorrhizal mycelia with the soil particles, permitting absorption of nutrient ions. Nutrient uptake of this kind is particularly common in forest soils of northern regions and skeletal substrata.

The process of nutrient absorption is essentially an exchange reaction between the root and nutrient ions. This reaction proceeds under the influence of excreted carbonic acid (Truog, 1928) or strong acidoids, that is, colloidal substances charged with hydrogen (Mattson, 1948). The hydrogen ions of roots are released to the soil in exchange for metallic cations, whereas the hydroxyl and bicarbonate ions are exchanged for anions. The liberation of some nutrient ions from their parent compounds is most likely accomplished by chelating agents produced in the decomposition of the epidermal tissues of roots and fungal mantles. The uptake of nutrients, moreover, is influenced by the oxidation-reduction potential that exists between the soil and the root (Merkle, 1955).

Under certain conditions the roots may release into the soil or soil solution not only H and OH ions but also metallic cations and ammonium. In sodium-rich alkali soils the soil may extract from the root system an appreciable amount of calcium and other cations. In time of severe drought, root systems excrete ammonia, thus manifesting the pre-death struggle of the plant (Prianishnikov, 1951). In soils treated with biocides and soluble fertilizer salts, exchange reactions between the soil and root system appear to be responsible for drastic modifications in the availability of nutrients. These modifications may either depress or abnormally stimulate the plant growth.

A critical deficiency of nutrients caused by their entire absence in the soil material is largely confined to forest soils derived from purely siliceous rocks. Otherwise, the shortage of nutrient elements results from an abnormally intensive cropping, such as occurs in nursery soils, depletion of soil by fire or erosion, or the adverse biological, chemical, and physical conditions that render nutrients unavailable.

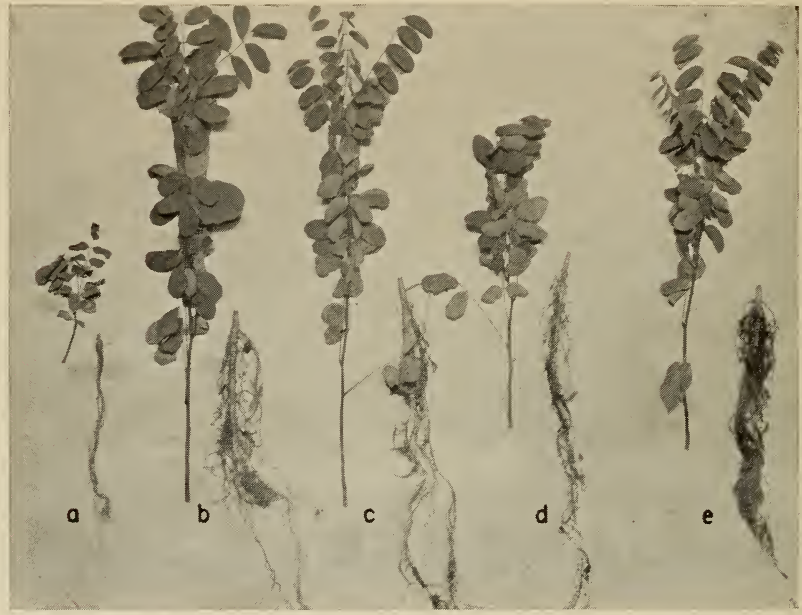


FIG. 9–10. Immobilization of available nitrogen by organic matter of a high carbon-nitrogen ratio: (*a*) six-month-old black locust seedling raised on a nursery soil treated with a heavy application of acid moss peat; (*b* to *e*) seedlings of the same age raised on plots that received 60 pounds per acre of elemental nitrogen in the form of sodium nitrate, ammonium sulfate, ammonium nitrate, and urea, respectively.

Microorganisms, especially bacteria, consume large amounts of soluble nitrogen which they incorporate into their cells and thereby deprive plants of this essential element (Fig. 9–10). Similarly, microorganisms may temporarily eliminate or reduce the supply of other nutrients. This condition of **biological fixation** is most likely to occur in soils of neutral or alkaline reaction, in which the activity of microorganisms is often very intensive. The biological fixation of nutrients may also be produced by slowly decomposing residues of heather and other forest vegetation developing raw humus layers of a high C/N ratio. This process reaches its climax in peat bogs where mineral salts are irreversibly fixed in the never-decaying thalluses of *Sphagnum* and other mosses. On strongly acid soils the content of available nitrogen may be decreased by the depressed activity of nitrifying bacteria. The absence of other specific microorganisms, especially mycorrhizal fungi, may also be responsible for unavailability of nutrients.

Both strong acidity and alkalinity of soils are conducive to **chemical fixation** of many nutrient elements. In acid soils the readily available monocalcium phosphate is changed into slowly soluble iron and aluminum phosphates, whereas in alkaline soils it is converted into a comparatively unavailable calcium phosphate (hydroxy apatite). Available potassium may be incorporated into secondary micas or some other not readily soluble compounds. A high content of lime or alkali salts may decrease the availability of iron, manganese, boron, and zinc. Frequently, certain ions minimize or offset the effect of other ions because of their "antagonistic" behavior (Stoklasa and Doerell, 1926).

When applied to a soil at an insufficient depth, or as a top dressing, organic matter may arrest the downward growth of tree roots and thus deprive seedlings of nutrients present at a greater soil depth (Fig. 9–11). Inadequate aeration causes conversion of nitrates into nitrites and, further, into elemental nitrogen. A number of other difficulties in the availability of nutrients, particularly sulfur and manganese, may arise due to the lack of oxidation. In fertilized soils of forest nurseries a deficiency of buffering colloids produces disturbances in the uptake of nutrients by plants due to "anastatic" or rapidly changing concentration of soil solution (Gola, 1910). Great

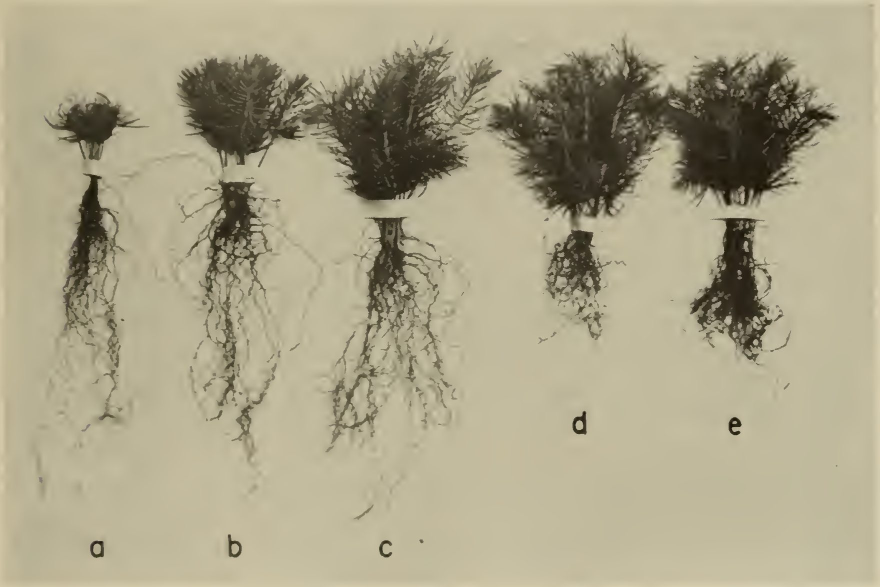


FIG. 9–11. Influence of surface applications of organic matter upon the development of Norway spruce seedlings: (*a*) quartz sand; (*b*) 325 pounds of complete fertilizer; (*c*) 650 pounds of complete fertilizer; (*d*) 650 pounds of fertilizer plus 20 tons of organic matter applied at the surface; (*e*) 650 pounds of fertilizer plus 40 tons of organic matter applied at the surface. (After Wilde and Wittenkamp, 1939.)

fluctuations in the moisture content of the soil may interfere with uptake of nutrients because of the erratic behavior of exchangeable ions. An increase in soil water content by rain or artificial irrigation induces a greater adsorption of calcium and other bivalent ions, with subsequent release of monovalent potassium, sodium, and ammonium; the drying of the soil has an opposite effect.

The factor which renders certain nutrients unavailable may either bring about starvation of trees or disrupt the proper ratio of nutrients and lead to unbalanced growth of trees. The latter condition is much more common in artificially fertilized nursery soils than in soils of natural forest stands. In older stands the acute deficiency of nutrients usually becomes pronounced at the age when trees attain their maximum nutritional demands; this age varies from 15 to 50 years, increasing with the tolerance of trees and the level of soil fertility.

Soil fertility is comparable to a power-utilizing machine. The presence of all nutrient elements in reasonable amounts is just as necessary for satisfactory growth of plants as the presence of the smallest screw or spring is essential for the efficient performance of a motor (Mitscherlich, 1923; Lundegårdh, 1954). This fact is all too often overlooked in the management of nursery soils and in fertilizer treatments of soils supporting plantations. In many instances the unavailability of a single nutrient element results in a waste of fertilizers containing other elements and aggravates rather than improves the state of soil fertility.

Because the adsorption of ions and assimilation of nutrients by plants are largely governed by the laws of mass action and chemical equilibrium, an excess of a certain element or compound in the soil may interfere with plant metabolism and lead to abnormal development. It has been noticed that an addition of a large amount of a certain nutrient element may bring to a critical level the deficiency of other nutrients. For example, application of potassium fertilizer greatly aggravates the deficiency of magnesium, an effect often observed in acid soils of long-cropped forest nurseries. Similarly, an acute shortage of potassium and magnesium may be produced by a generous application of nondolomitic limestone or calcium carbonate sludge from paper mills. Within certain limits, nursery soils with a low level of fertility but a balanced ratio of nutrients produce better planting stock than soils treated with one-sided application of fertilizers.

An instructive picture of the effect of nutrient balance on the growth of roses in hydroponics was reported by Turner and Henry (1939). According to their experiences the optimum growth during the period of May to August is achieved with a solution containing 450 ppm. of nitrogen and 150 ppm. of potassium. During the darkest months of December and January the concentration of nitrogen must be lowered to 150 ppm., whereas that of potassium must be raised to nearly 700 ppm. Similar relationships undoubtedly hold true in regard to the balance of other elements, but no such extreme variation in the ratio of nutrients is ever required by plants outside of hydroponic cultures. The normal growth of plants proceeds under reasonably uniform conditions of radiation, and in a buffered soil the balanced nutrition is facilitated, to a certain degree, by the ability of plants to absorb nutrients selectively.

It may be accepted axiomatically that nutrients are present in a balanced ratio in soils of all well-growing forest stands. This balance is maintained by the combined effect of buffering colloids and microorganisms. In this respect a forester can well agree with the credo of Russell (1950, p. 135), that "a fertile soil is one which contains either an adequate supply of plant food in an available form or a microbial population which is releasing nutrients fast enough to maintain rapid plant growth."

TOXIC AGENTS

The productivity of a soil may be limited, not only by a deficiency of nutrients, but also by the presence of certain ions or compounds in toxic concentrations. The toxicity of a soil is manifested either by an immediate injury of plants or by their gradual deterioration. Soil toxicity is most dangerous during the initial period of tree growth.

Under natural forest conditions, soil toxicity is of rather rare occurrence. A toxic concentration of the soil solution is sometimes encountered in prairie-forest regions, particularly in depressions receiving run-off water. Soils derived from calcareous rocks may contain carbonates of calcium and magnesium in amounts sufficient to be detrimental to trees, especially to acidophilous conifers. Hydrogen sulfide accumulating in poorly drained soils may exert a depressing effect on the growth of trees. A high content of ferrous iron in the gley layer is believed to be harmful to some plants. High concentrations of soluble aluminum and manganese in the accumulative layers of podzol soils appear to arrest the downward penetration of roots. Most of these adverse conditions, however, seldom play a significant part in the growth of natural forest stands.

The effect of toxic agents attains its utmost importance in soils of forest nurseries. Soluble salts frequently accumulate in toxic concentrations by evaporation in the surface layer of sandy nursery soils treated with commercial fertilizers. The excess of soluble salts produces "burning" of the roots, which become shriveled and black in color (Fig. 9–12). Depending on the degree of injury, the seedlings may either wilt or produce secondary roots and recover. A similar type of injury is encountered in treatments with sulfuric and other acids. In nurseries irrigated with hard water, soluble bicarbonates may be brought to the soil surface by evaporation and form a carbonate crust which may lead to destruction of the entire seeding. Decomposition of animal manures or sludge fertilizers may release ammonia in an injuriously high concentration, the process being enhanced by a high temperature and abundant supply of soil moisture.

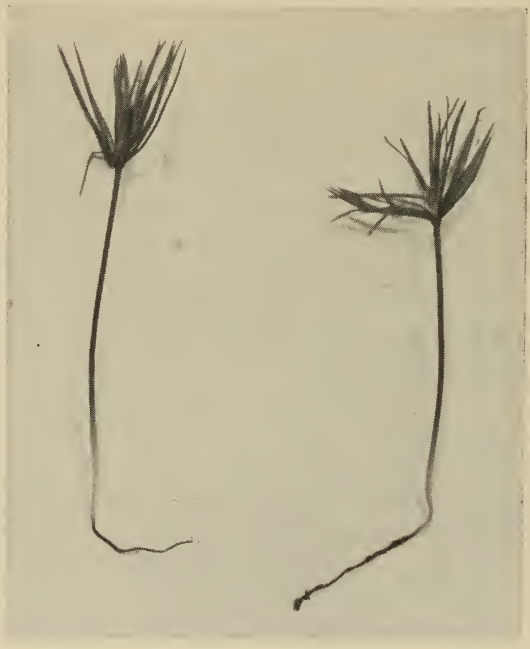


FIG. 9–12. Burning of seedling roots by soluble salts in high concentration. Symptoms are similar to those produced by toxic substances, such as lead arsenate and calomel.

A toxic quantity of sodium may accumulate in the soil when nitrogen deficiency is corrected by regular applications of sodium nitrate. This is because the nitrate ion is utilized by plants, whereas sodium is retained by the colloidal fraction of soil. The burning of brush is often the cause of barren spots in recently established nurseries or on cut-over lands because of the toxicity of potassium carbonate in wood ashes. Fresh sawdust applied in large quantity depresses the growth of seedlings. This effect is caused by the high carbon-nitrogen ratio and the presence of toxic substances such as oils and resins.

A toxicity of soil in various degrees may result from the application of various fungicides, insecticides, and herbicides. Injury from creosote is common in nurseries using impregnated boards for bed construction. The injury is usually confined to a narrow strip of seedlings adjacent to the frames. The oil and grease from nursery equipment is sometimes responsible for the deterioration of nursery stock. Discarded waste, such as garbage, cinders, soap water, and cleaning solutions cause decadence of trees around dwellings. A concentration of animals on small areas, such as found in mink farms, may also be lethal to trees.

The following common remedies are used in counteracting soil toxicity: plowing, rototilling, scraping off surface soil, tile drainage, artificial irrigation, raising of crops tolerating high concentrations of salts, green manuring, use of sprays or injections of chelated iron compounds, such as iron citrate, and the application of acid peat, peat high in bases, raw humus, liquid humates, lime, wood ashes, and fertilizers, especially nitrates, ammonium sulfate, ammonium phosphates, and low grade superphosphates.

IONIC REACTIONS OF FOREST SOILS

Cation exchange. When a soil sample is leached with an aqueous solution of ammonium sulfate, the leachate shows some loss of ammonium and a gain in the content of calcium, magnesium, potassium, and other cations. This is because the colloidal fraction of the soil has exchanged some of its adsorbed cations for ammonium ions of the solution. An analysis of the leachate after such an exchange reaction will prove that the solution has preserved its original ionic concentration; hence the loss of adsorbed ammonium was compensated for by the release from the soil of an equivalent amount of other cations. This process may be illustrated by the following equations in which x represents a micelle or a portion of the large anion of the colloidal exchange material:

$$(NH_4)_2SO_4 + Cax \leftrightharpoons (NH_4)_2x + CaSO_4$$

or

$$(NH_4)_2SO_4 + K_2x \leftrightharpoons (NH_4)_2x + K_2SO_4$$

A similar reaction will take place if a solution of some salt other than ammonium sulfate is used in treatment of the soil. For example, an application of a solution of sodium nitrate to a nursery soil will produce the following reactions:

$$2NaNO_3 + K_2x \rightleftharpoons Na_2x + 2KNO_3$$

or

$$2NaNO_3 + Cax \rightleftharpoons Na_2x + Ca(NO_3)_2$$

The salts in solution, for example potassium chloride, replace from acid soils not only bases but also hydrogen:

$$2KCl + H_2x \rightleftharpoons K_2x + 2HCl$$

Other effect of an addition of potassium chloride would involve liberation of bases:

$$\boxed{\quad\text{micelle}\quad}\begin{matrix}\text{Ca}\\ \\ \text{Na}\end{matrix} + 3KCl \rightleftharpoons \boxed{\quad\text{micelle}\quad}\begin{matrix}\text{K}\\ \text{K}\\ \text{K}\end{matrix} + CaCl_2 + NaCl$$

As a result of ionic exchange, an application of fertilizers usually leads to the adsorption of the positively charged cations with the release of other bases or hydrogen into the soil solution. The released cations combine with the free anions to form acids, alkalies, and salts. The acids, alkalies, and easily soluble salts, including HCl, H_2SO_4, H_2CO_3, NaOH, KCl, Na_2CO_3, and $CaCl_2$, may be leached from the soil by percolating water; the difficultly soluble compounds, such as $CaCO_3$, $FePO_4 \cdot 2H_2O$, and $AlPO_4 \cdot 2H_2O$, remain in the soil. The replacement of hydrogen by the calcium ion in monocalcium phosphate is an important example of an exchange reaction which leads to **phosphate fixation,** that is, conversion of a readily soluble phosphate salt to the insoluble tricalcium phosphate:

$$CaH_4(PO_4)_2 + 2Cax \rightarrow 2H_2x + Ca_3(PO_4)_2$$

The colloidal fraction of soils, capable of retaining and exchanging cations, is termed the "base exchange complex;" "ion exchange compound," or simply **exchange material.** This exchange material exists either in mineral or organic form. The mineral or **clay fraction** consists of aluminum and iron silicate clay minerals; the organic or **humate fraction** is a lignin-like humus compound. In spite of their different composition, both materials show considerable similarity. Their chemical structure is based upon tetravalent elements, silicon and carbon. The mineral exchange material consists of microscopic and ultramicroscopic crystals whose porous structure allows the penetration of water and ions as do the organic colloids. With respect to the retention of nutrients both fractions act inseparably in the soil and their common effect is measured in terms of **exchange capacity.**

The relative proportion of various ions adsorbed by the exchange compound depends partly upon the **energy of adsorption** of these ions and partly upon their concentration in the solution.

The energy of adsorption or "replacing power" usually increases with valence and atomic weight. Therefore, the Ba ion is more readily adsorbed by the soil than the Ca, Mg, K, or Na ions, the latter having the lowest energy of adsorption. However, hydrogen is an exception. The replacing power of the most important ions is given in the following order of diminishing activity:

$$H^+ \quad Ba^{++} \quad Ca^{++} \quad Mg^{++} \quad K^+ \quad NH_4^+ \quad Na^+$$

The energy of adsorption is not necessarily a criterion of the stability of the ions in the exchange compound because exchange reactions are governed by the relative concentration of solution and the ratio of the ions present. In strong solutions, K and Na ions may exhibit a higher replacing power than Ca and Mg ions. The nature of the exchange material may also modify the behavior of replaceable bases (Mattson, 1948). Moreover, the outcome of exchange reactions may be complicated by negative charges not related to the isomorphous replacements in the lattice. All in all, as concluded recently by Wiklander (1955), "there is no simple universal order of the replacing power of cations."

The very union of exchangeable components is not of a catholic order, and, like many such unions, is not free from erratic escapades or **hysteresis.** By and large, the marriage and divorce of the ions to the micelle are determined by the **principle of mass action.** According to this principle, any ion adsorbed by the exchange material may be replaced with another ion occurring in the soil solution in considerable excess. Consequently, all of the bases and hydrogen may be replaced in the soil by ammonia if the soil is repeatedly leached with a solution of ammonium sulfate or ammonium acetate. The ionic reactions of this kind can best be compared to the dynamics of avalanches which so often replace the detritus at the foot of the hill with debris of fresh material wrenched from the upper slopes.

The understanding of exchange reactions explained many relationships incomprehensible to early investigators; it has revolutionized the whole concept of plant nutrition and placed fertilizer practice upon a firm scientific foundation (Way, 1850; Gedroiz, 1929; Wiegner, 1929).

The exchange capacity of soils is commonly determined by a slow leaching of the soil sample with a normal solution of calcium chloride adjusted to pH 7.0. After washing out the excess of chlorides with distilled water, the adsorbed calcium is removed by leaching with a normal solution of ammonium acetate and determined by precipitation with sodium oxalate (Chapman and Kelley, 1930), or by the use of the flame photometer. The results are, as a rule, expressed in terms of milliequivalents. Such presentation places the adsorbing capacity of soils on an equal basis in regard to all cations, and thus eliminates the complications arising from the differences in atomic weights and valences. For example, the atomic weight of calcium is 40 and its valence is 2; therefore one milliequivalent of calcium is equal to $(40 \div 2) \times 0.001$, or 0.020 g. of calcium. If a soil has a base exchange capacity of 5 m.e. per 100 g., it can adsorb or hold in replaceable form 5×0.02, or 0.1 g. of calcium per 100 g., or 0.1 per cent. Since the weight of the surface soil layer of a sandy loam or a light loam soil (6-inch layer) is about 2,000,000 pounds per acre, the amount of adsorbed calcium will be 2000 pounds per acre. According to similar calculations, the same soil would adsorb 1200 pounds of magnesium and 3900 pounds of potassium per acre.

Silvicultural importance of exchange colloids. In the opinion of Wiklander (1955), ionic exchange may be considered "as the most important of all the processes occurring in a soil." The weathering of rocks, formation of secondary minerals, development of the soil profile, loss of nutrient ions by leaching or their fixation in insoluble form, and uptake of nutrients by root systems—all are related to the activity of exchangeable ions.

Under natural conditions, the exchange material of soils is saturated predominantly with hydrogen and calcium, occurring in various proportions. The application of fertilizers, however, may greatly change the natural ratio and largely saturate the soil colloids with other ions, such as those of ammonium, potassium, or sodium. Soils whose exchange material is saturated with bases have a neutral or alkaline reaction and are referred to as **base saturated soils.** The soils whose exchange material is largely saturated with hydrogen are of acid reaction and are called **base unsaturated soils.**

The high water-holding capacity of exchange material and the influence of adsorbed bases on the development of structural aggregates exert a profound influence upon the physical properties of soils.

The exchange material acts as a storehouse in which bases are preserved in a form available to plants and yet not easily removable by water. It is believed that carbonic acid, excreted by the root hairs, exchanges its hydrogen for ammonium, potassium, and other bases of the exchange compound. These enter the soil solution and form with liberated acid radicals the soluble bicarbonates which are utilized by the root systems.

The base exchange capacity of soils determines the rate at which fertilizer may be safely applied to soils of forest nurseries and plantations. On fine-textured soils, rich in organic matter and having an exchange capacity of about 15 m.e. per 100 g., an application as high as 1200 pounds of total salts per acre may be a safe and economical practice, for most of the nutrient cations will be adsorbed and preserved from leaching by the base exchange material. In a sandy soil with a capacity not exceeding 5 m.e. per 100 g., a direct heavy application of fertilizers would be very uneconomical, as most of the applied nutrients would be leached out before the seedlings could utilize them. Hence, on such soils, the applied fertilizers must be incorporated in composts or in the tissues of catch crops, or added to the soil in small portions as liquid fertilizers distributed over the whole period of stock development (Wilde and Kopitke, 1940). In order to attain a greater freedom in fertilizer practice, the general tendency in management of sandy nursery soils is to increase the soil exchange capacity by the application of clay, peat, or other organic materials.

Because of the strong tendency of the exchange material to react with the dissociated cations of the soil solution, some harmful constituents may be eliminated from the soil by introduction of desirable ones. In this way, the application of potassium fertilizer may free a nursery soil of toxic Na ions accumulated from repeated applications of sodium nitrate. The treatment of nursery soils with sulfur is essentially a similar process in which the hydrogen ions of the sulfuric acid liberate the soil from an excess of calcium.

A knowledge of the exchange capacity is useful not only in fertilizer practice, but in the entire technique of forest soil utilization, especially in the selection of species for planting. The exchange capacity of the entire soil profile is of particular significance since it summarizes the effects of both mineral and organic colloids and reflects the physical, chemical, and genetic nature of the soil (Chandler, 1939). Table 9–1 presents the exchange capacity of several typical profiles of forest soils.

Anion adsorption capacity. The colloidal fraction of some soils carries positive charges that adsorb the negatively charged anions of chlorine, nitrate, phosphate, and other radicals. The positive charges emanate from hydrated iron and perhaps aluminum compounds located at the edges of clay minerals.

The anion exchange capacity may influence the development of soils by counterbalancing the positive charges and thus permitting the system to reach the **isoelectric point.** If this state of equilibrium is attained, a decrease in the pH value will impart to the soil a positive charge, whereas an increase in the pH value will impart a negative charge. Soils of this type, called **amphoteric soils,** appear to be particularly common in the tropical zone.

From a practical standpoint, the capacity of soils for retention of anions is largely important in regard to the monovalent $H_2PO_4^-$ ions. In fact, it has been suggested that the anion exchange capacity be defined on the basis of the amount of phosphate bound at a certain pH value. The nitrate and chlorine ions do not appear to be held by the soil sufficiently tightly to affect the nutrition of plants. It seems that the fate of phosphates is influenced by the participation in the anionic exchange of humic acid, for the presence of humates usually leads to the release of adsorbed phosphorous. At the present state of knowledge the anionic exchange capacity of soils has a very restricted significance; in most forest soils this property is completely overshadowed by purely chemical and biological fixation of nutrient ions.

TABLE 9–1

EXCHANGE CAPACITY OF REPRESENTATIVE GENETIC TYPES OF FOREST SOILS

Weekly podzolized sand		Podzol loam		Nut-structured grood loam		Gley loam	
Horizon	m.e. per 100 g.	Horizon	m.e. per 100 g.	Horizon	m.e. per 100 g.	Horizon	m.e. per 100 g.
A_0	13.7	A_{00}	76.3	A_{00}	87.30	A_0	65.5
A_1	7.8	A_0	83.2	A_1	21.50	A_1	32.2
A_1	5.7	A_2	4.3	A_2	6.72	A_2	6.7
A_2B	2.1	B_1	7.4	A_2B	11.04	B	11.7
A_2B	1.9	B_1	15.6	B_1	17.57	BG	8.3
C_1	0.4	B_2	15.9	B_2	13.66	G_1	6.1
C_2	0.5	C	12.1	C	7.06	G_2	5.4

Chelating agents. The availability of nutrients is influenced by the so-called chelating effect of organic anions which form stable complex ions with calcium, iron, aluminum, manganese, copper, and zinc (Martell and Calvin, 1952). For example, addition of a certain chelating agent (EDTA or ethylenediaminetetraacetic acid) will prevent precipitation of $CaCl_2$ by oxalic acid. It also may produce a salt-splitting reaction which will break calcium oxalate into complexed calcium and free oxalic acid. In a similar manner chelating ions may dissolve iron and aluminum and thereby release available phosphorus from otherwise insoluble iron and aluminum phosphates.

Of great importance is the fact that chelating agents, such as citrate, tartarate, and malate, can be produced by soil microorganisms from organic materials of wide origin, including ordinary starch. It is entirely probable that in nutrition of deep-rooted woody plants chelating agents are provided by the decay of superficial tissues of roots and dead mycotrophic organs. This mechanism may be responsible for the enormous capacity of forest trees to absorb phosphorus and other nutrients from difficultly soluble compounds.

The old practice of adding iron citrate or iron tartarate salts to chlorotic trees is essentially based on the inability of complex iron to form an insoluble precipitate (Steward and Leonard, 1952). The beneficial effect of the addition of organic remains or liquid humates on the availability of nutrients is well known to nurserymen operating on calcareous soils. In some instances, green manures appear to serve as the source of chelating compounds that corrected the little-leaf symptoms of zinc deficiency in tree seedlings (Hoagland, 1944). Judging from agricultural experiences (Mehlich and Drake, 1955), the growth of certain crops is stimulated when they are grown together with other plants of presumably greater chelating efficiency. Experiences of silviculturists with mixed stands, soil-conserving understories, and even accidental intrusions of alien seedlings in nursery beds provide many examples suggesting a growth-stimulating effect of chelating agents.

Oxidation-reduction potential. Originally, oxidation was assumed to involve either the addition of oxygen or the removal of hydrogen. In time, however, it was found that some reduced compounds, for example ferrous iron, may be oxidized by many substances not including oxygen. Consequently, oxidation and reduction processes are regarded in terms of electron migrations. Oxidizing properties are due to a tendency to part with electrons, and reducing properties to a tendency to take up electrons. When one substance is oxidized (parts with electrons) another is always simultaneously reduced (takes up the electrons liberated), for example:

$$2FeO + O_2 \rightleftharpoons Fe_2O_3$$

or

$$Fe^{++} \rightleftharpoons Fe^{+++} + e$$

As a result of this reaction, the system is enriched by one free electron (e) that may be accepted by another atom possessing an extra positive charge.

The soil includes a considerable number of "flighty" elements, such as N, S, Fe, Mn, P, Ti, and Cu, which can change their valence. These elements, together with oxygen, hydrogen, and organic compounds, determine the course of oxidation-reduction reactions. Whenever there is a tendency of some electrons to be emitted or accepted, the imbalance is expressed by the **electromotive force** (emf). This force can be measured by means of a gold or platinum electrode, thereby expressing in volts the **oxidation-reduction** potential (OR) or the ratio of the total oxidizing intensity to the total reducing intensity of the medium:

$$\mathrm{OR} = E_0 - 0.06 \log \frac{(\mathrm{Ox})}{(\mathrm{Red})}$$

As indicated by the term "potential," this formula under certain circumstances expresses an enormous supply of latent energy. One of the most dramatic outward manifestations of a high oxidation-reduction potential is presented by deposits of coal with imbedded pyrite and marcasite. When such deposits are exposed by excavation, the minerals are oxidized to ferric iron and sulfuric acid by mere contact with atmospheric oxygen. The heat evolved in the oxidation occasionally is so great that the piles ignite spontaneously.

In the electrometric determinations of the oxidation-reduction potential with a platinum electrode, a calomel half-cell is used as the reference cell, but the results are usually expressed in relation to the normal hydrogen electrode which is taken as zero. Because the oxidation-reduction potential is influenced by the activity of hydrogen ions, the results are converted to pH 7.0 by assuming that a decrease of one pH value unit of the system raises the OR potential by about 60 millivolts. The use of 60 millivolts, however, is a rough approximation, for in some systems the correct conversion factor varies from less than 50 to 100 millivolts. The deviations are especially great in heterogeneous biological entities such as humus layers of forest soils (Lafond, 1950).

Careful attention should be paid to the difference that exists between the terms "oxidation-reduction" potential and "reduction-oxidation" or "redox" potential. These terms are unhappily confused in the literature and in the common usage. Not infrequently the meaning of the oxidation-reduction potential is misinterpreted to the effect that its high positive value refers to an oxidized medium.

Actually, a poorly oxygenated ground water, reduced by suspended organic colloids and ferrous iron, is a medium eager to part with electrons. Hence, it has a high **oxidation-reduction** potential, such as +100 millivolts at pH 7.0, and a very low negative **redox potential** of −100 millivolts. Vice versa, a well-oxygenated spring water has a low oxidation-reduction potential, but a high redox potential. Because a reduced condition is usually characterized by a negative sign, it is more convenient to refer consistently to the briefer terms: redox potential or, simply, reduction potential.

One of the earliest determinations of the redox potential in soils was made by Gillespie (1920), who showed that a reduced condition rather than acidity was responsible for poor growth of plants on waterlogged soils. In the course of the following years the reduction-oxidation conditions of soils were studied by a number of investigators; their achievements were summarized by Merkle (1955).

The reduction-oxidation equilibrium in soils to a large degree determines the course of microbiological processes, for certain groups of microorganisms have definite RO preferences. This relationship is likely to be particularly important in forest soils, as it may influence the development of humus layers and, in turn, many other aspects of soil fertility and forest growth.

The value of the redox potential is appreciably modified by the content of free oxygen in the soil water and therefore reflects the degree of soil aeration. The soil aeration, in turn, determines the all important chain reactions starting with oxidation of iron and manganese and climaxing in the release of carbonic acid, nitrates, and sulfates. A very low negative redox potential is correlated with the high concentration of toxic reduced substances, deterioration of roots, and poor growth of trees. These conditions were found to be particularly pronounced in soils of abandoned beaver flowages that remain treeless for several decades after the removal of impounded water (Wilde, Youngberg, and Hovind, 1950). In soils with a high content of manganese a high redox potential may lead to the oxidation of the entire supply of ferrous iron, thereby causing chlorosis of plants.

Unfortunately the knowledge of oxidation-reduction conditions of soils is still far from being complete. A considerable variability of the redox potential in different soil horizons and in different periods of the growing season, as well as technical difficulties involved in the determination of the potential *in situ*, are the major obstacles which have thus far prevented the establishment of definite numerical limits. More concrete information, however, is available in regard to E_h values of ground water underlying organic soils of different origin. The results of several studies (Wilde and Randall, 1951; Pierce, 1953) showed a close correlation of the redox potential with the degree of stagnation or oxygenation of ground water, the type of forest cover, and the rate of growth of forest stands. The fact that ground water presents a homogenized and poised suspension is a fortunate detail which greatly facilitates electrometric analysis.

As far as possible, men are to be taught to become wise not only by books, but by the heavens, the earth, oaks and beeches.
—Comenius, *Great Didactics,* 1632

10

Relation of forest vegetation to soils

Soils and men. The relationship between soils and forest vegetation has long been known to people of North America. The early settlers of the Lake States region, for example, considered "white pine soils" as fair pasture, "Norway pine soils" as mediocre fields, and "jack pine soils" as soils unsuited for agricultural use (Mayr, 1890). At present the expression "hardwood land" commonly implies a soil of a high productivity rating, whereas the expression "hemlock land" refers to a leached soil of questionable fertility. "Balsam flats" in the farmer's mind are associated with heavy, moist, and cool soils, suitable for grazing rather than for cultivation.

Writes Hilgard (1906):

> In the Southern States, the classification of uplands into "pine lands" and "oak lands" is universal, and is associated with certain limits of valuation, both by assessors and purchasers. Within each of these two classes, however, there are well-defined gradations of cultural value according to the kind (species), e.g., of pine or oak that occupies the ground, either alone, or in mixture with other trees whose presence or absence is considered significant. In the case of "bottoms" or alluvial lands, corresponding distinctions and classifications obtain; we hear of hickory, beech, gum, and cherry bottoms, hackberry hummocks, etc., each name being associated with certain cultural values or peculiarities well understood by the farming population.

In numerous instances the interdependence of soil, plants, and animals has penetrated deeply into the life of man and has found a masterful expression in words of great writers. A few lines from "Markens Gröde" by Hamsun may be quoted as an example; they describe the environment of the desolate "Almenning," no man's land in the author's native Norway:

> Man moves along the western side of a valley; wooded ground with hardwood trees among the spruce and pine, and grass beneath. Hours of this, and twilight is falling, but his ear catches the faint purl of running water, and it heartens him like the voice of a living thing . . . He moves down and there is a green hillside; far below, a glimpse of the stream, and a hare bounding across. The man nods his head, as it were approvingly—the stream is not so broad but that a hare may cross it at a bound. A white grouse sitting close upon its nest starts up at his feet with an angry hiss, and he nods again; feathered game and a fur; a good spot this. Heather, bilberry, and cloudberry cover the ground; there are tiny ferns, and the seven-pointed star flowers of the wintergreen. Here and there he stops to dig with an iron tool, and finds good mould, or humus soil, manured with the rotted wood and fallen leaves of a thousand years. He nods, to say that he has found himself a place to stay and live . . .

Trained forester as well as soil expert may bow before such a comprehensive description of land and life.

In the initial stages of ecological research, the knowledge of rural people helped to establish a number of important relationships between soil and vegetation (Kruedener, 1927). Unfortunately, some of the strictly local observations were accepted as the basis for broad generalizations and unwarranted classificational schemes. With the accumulation of technical knowledge the students of forest soils came to realize that there is more in the problem of the soil-forest interdependence than meets the eye, and what does meet the eye is sometimes grossly misleading. They learned that the influence of various soil properties is complicated by several extra-edaphic conditions, particularly the state of climatic factors and the dynamics of forest vegetation. The following analysis of different aspects of the soil-forest relationship should help to remove some of unqualified inferences which served in the past to confuse rather than to enlighten the forest manager.

Productive capacity of soils as a function of climate. The soil is not so much a source as a transformer of life forces, such as heat, water, oxygen, and nitrogen. Because of this, soils of similar geologic origin, texture, drainage features, content of nutrients, and other properties may greatly vary in their adaptation to forest vegetation and productive capacity under different climatic conditions (Daubenmire, 1947; Oosting, 1950; Lundegårdh, 1954).

It is well agreed by foresters practicing in continental climates that coarse sandy soils do not provide satisfactory conditions for the growth of spruce. Nevertheless, in the cool and humid environment of Canada and Siberia such soils often support stands of spruce species that produce as much as 60 cords per acre at the age of one hundred years. Under climatic conditions of Bohemia, characterized by a relatively short growing season, Austrian pine exhibits slow growth and signs of malnutrition on soils with a low content of nutrients; the same species, however, grows satisfactorily on barren sites in the Mediterranean region where the growing season is considerably longer. Black walnut near the northern boundary of its distribution is confined to rich soils of circumneutral reaction; this exacting tree attains large dimensions and produces abundant nut crops on strongly acid and leached soils of southern United States.

Perhaps the most striking picture of the modifying influence of climate on the soil-forest relationship is provided by white oak. This species is distributed on upland silt loams from western Minnesota to southern Indiana and exhibits the whole gamut of climate-enforced transitions in density, stem form, and rate of growth. In the proximity of the blackearth high summer temperatures and sparse rainfall raise the concentration of the soil solution to the level of toxicity; white oak stands here are of the savannah-like open type, with dwarfed, scraggly stems yielding only a few cords of firewood per acre. With moderation of continental extremes the growth of white oak undergoes gradual improvement, and near the Iowa-Wisconsin-Illinois boundary it attains the dimensions of a fair timber tree yielding about 12 Mbf per acre. In the mild environment of the Indiana hills, bordering the Ohio River, stands of white oak attain the enormous volume of 40 Mbf per acre of nearly cylindrical veneer logs (Fig. 10–1).

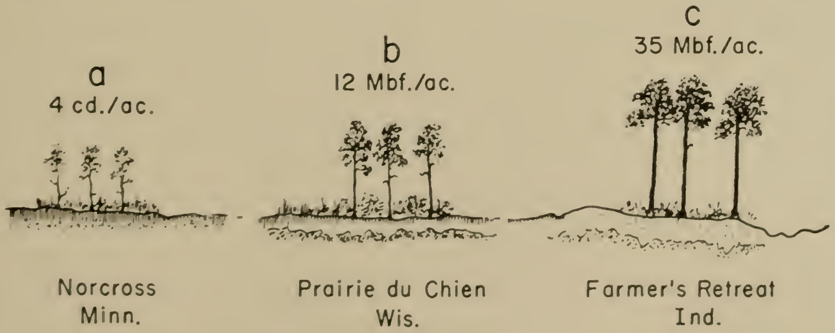


FIG. 10–1. Variation in the growth of white oak on upland silt loams under the influence of different climatic conditions: (*a*) degraded chernozems of western Minnesota; (*b*) leached prairie-forest soils of western Wisconsin; (*c*) yellow podzolic planosols of southern Indiana.

The modifying influence of the local physiographic conditions deserves particular attention in classification of forested soils in rolling or hilly topography. Such soils usually provide striking illustrations of the effects of the three major edaphic factors: water, aeration, and nutrients (Fig. 10–2).

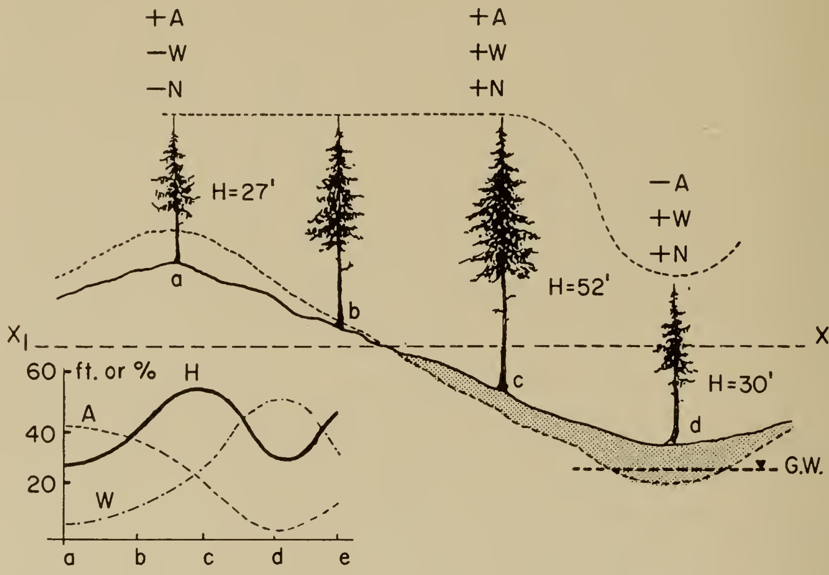


Fig. 10–2. Effect of topography on moisture (*W*), aeration (*A*), and nutrient content (*N*) of soil and the resulting growth of trees. Line X_1-X_2 delineates positive topography, subject to denudation, and negative topography, subject to deposition of eroded materials. Diagram presents the average heights (*H*) in feet and state of moisture and aeration at field capacity in per cent by volume.

The top and upper slopes of a ridge or a mound represent elements of so-called positive topography. Soils overlying this portion of the relief receive the least rain water and are subject to denudation, which decreases the supply of available nutrients. Consequently, such soils often support forest stands of low rate of growth. On the other hand, the negative topography of lower slopes receives run-off water and fertilizing products of erosion—mineral colloids, humus, and soluble salts. As the result of this enrichment of the soil, forest stands increase their height growth, or, as foresters say, "Trees level the relief with their crowns." With the descent to a depression the water accumulates in excess, and the growth of trees drops abruptly in accordance with the rapidly decreasing soil aeration. In some instances the accumulation of water is associated with an injurious increase in the content of soluble salts. Thus, the height growth and the yield of forest stands on a topographical complex tend to follow a sinusoidal curve.

The outlined relationship is very common in the temperate region (Morozov, 1912; Russell, 1950) and serves as the key to survey of hilly forest lands. Yet it does not hold true in every climate. In the humid environment of podzols the curve of forest growth may be entirely reversed, for hard maple, basswood, white ash, and other deciduous trees attain their best development on the positive portions of morainic ridges covered with permeable, weakly podzolized soils. The rate of growth of these species, however, drastically declines on soils of the lower slopes because of severe podzolization. A similar trend may be encountered in hilly lands of tropics, where soils are predisposed to the development of lateritic crusts.

These examples should suffice to stress the all-important fact that climate, topography, and soil are inseparable growth factors. Pfeil's maxim, "No general rules in forestry," was not intended by its author to introduce into forest management a spirit of anarchistic disorder but to protest against unjustified generalizations based on local experiences, generalizations which disregarded the modifying influence of environmental factors and contaminated silvicultural theory with an untold number of controversies. Therefore, it is well to remember that all examples of the forest-soil relationship quoted in this chapter are valid only within specific climatic regions.

Obvious and concealed relationships. The tie between soil and forest vegetation is not always detectable by mere ocular observation of forest stands and soil profiles; at times it may be revealed only by careful analyses of soils, rate of forest growth, and quality of timber (Coile, 1952).

Obvious relationships are exemplified by jack or Scotch pine on sandy soils, hard maple or basswood on fine-textured soils, and alder on muck or wet soils. Relationships of this kind are evident even to a nontechnical man who has had some contact with the forest; they can easily be explained by assuming that jack and Scotch pines do not encounter any competition on sandy soils, that maple and basswood require the abundant supply of nutrients of loam soils, and that alder needs the moisture of swamp soils.

Many species of trees occur on soils which vary greatly in their texture, drainage, and fertility. For instance, white pine or aspen occur on sandy as well as fine-textured soils, on well-drained and poorly drained soils, on soils rich or soils poor in nutrients. A careful investigation, however, shows that white pine avoids the poorest sandy soils, such as wind-blown sands, the soils of recently burned areas with a low content of organic matter, and bogs with stagnant water. If the study is not limited to the distribution of trees alone but covers also the rate of growth, capacity for natural regeneration, and value of produced wood, it will be found that the optimum growth of white pine is confined to soils adequately supplied with air, moisture, and nutrients. Similar qualifications are applicable to aspen and other tree species (Wilde and Paul, 1951). Moreover, nearly all tree species exhibit on different soils dissimilarities in the form of their stems, crown, and root systems. Hilgard (1906) describes as many as four distinct morphological varieties of post oak and black oak found on upland loams, sandy ridges, flatwoods, and black calcareous soils of the South (Fig. 10–3). Duerr *et al.* (1956) have detected that the vigor and prospective diameter growth of bottomland hardwoods are strikingly reflected in the appearance of the bark. Bark features stand out so conspicuously that some other characteristics, such as site, age, and root system, can largely be ignored (Fig. 10–4).

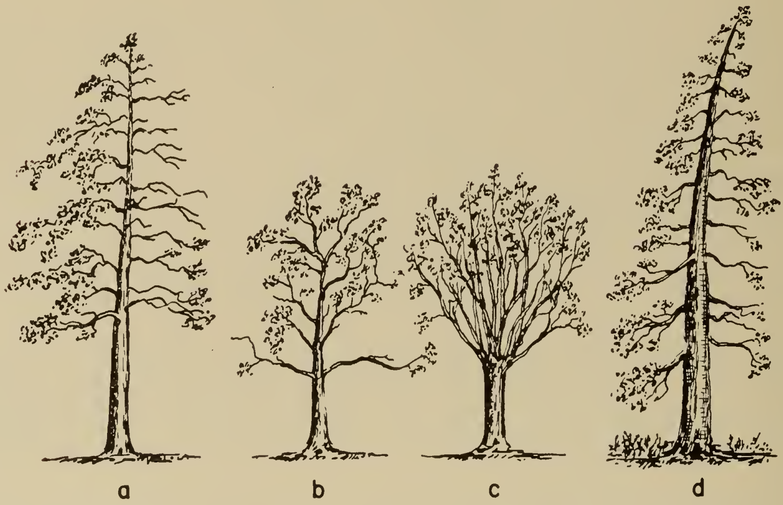


Fig. 10–3. Extreme forms of post oak on different soils: (*a*) upland loam; (*b*) sandy ridges; (*c*) flatwoods; (*d*) prairie. (After Hilgard, 1906.)

Mass action of the forest. The occurrence of a tree species on a certain soil type depends to some extent on the composition of surrounding forest cover and on the size of the soil area. A few acres of loam or clay soil in a region of sandy deposits occupied by pines often do not support exacting hardwoods or spruce, because the pines form a barrier against the intrusion of other species. The

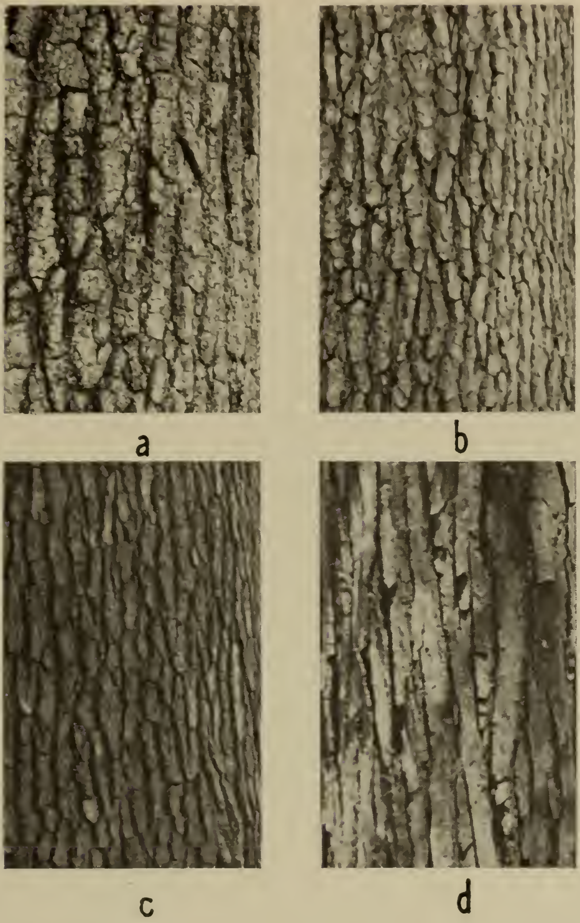


FIG. 10–4. Relationship of bark and the vigor of trees, an index of prospective diameter growth (as seen in a sweetgum): (*a*) tree of high vigor; (*b*) tree of medium vigor; (*c*) tree of low vigor; (*d*) decadent tree. (After Duerr, Fedkiw, and Guttenberg, 1956.)

tongues of lacustrine clays, protruding locally through sandy plains of glacial outwash, provide striking examples of this deviation from the general pattern of forest distribution. For the same reason patches of gravelly eskers or other coarse soils, spread in fine-textured moraines, are often occupied by exacting species rather than trees common to sandy soils.

Thus, the distribution of forest vegetation at times resembles colloidal exchange reactions whose outcome, according to the law of mass action, is determined by the constituent dominating the reaction medium. Besides the mere isolation of interspersed soils from the source of seed, forest stands exert biological pressure against intruders by developing unfavorable forms of humus, building up population of damping-off fungi, and harboring fauna hostile to trees of foreign origin (Wilde, 1954).

The physical and biological barriers of existing forest cover may play a far-reaching part in the distribution of both trees and ground-cover plants. There is reason to believe that the northwestern boundary of hemlock in the United States is established not by conditions of climate and soil but by the combination of biotic factors. Similarly, occasional absence of wintergreen, *Gaultheria procumbens*, on podzolized sandy soils of the Lake States region can be explained by the isolating effect of hardwood forest.

The possession of the land by the predominant vegetation is not without restrictions imposed by environment. If the productive capacity of interspersed soils falls too far below the requirements of the ruling plant associations, such soils may be invaded by less-exacting species, the wind, water currents, and birds sponsoring the settlement. Unique examples of the overruling effect of environmental factors are found in the prairie-forest transitions of the American Midwest. For many centuries this territory presented a mosaic of prairie grasses and oak-hickory stands. Yet, in the heart of this region there occur small areas of sandstone outcrops that support hemlock and yellow birch with their faithful ground-cover associates—partridge berry and Canada mayflower. These invaders from a hundred-mile-distant northern forest developed extra-zonal podzols with typical raw humus, a soil totally alien to the regional landscape.

Forest succession. No forest stand is in a stable equilibrium, for trees growing at a close spacing are in a constant mortal struggle for light, moisture, and nutrients. This struggle is especially pronounced in mixed stands where trees are exposed to intraspecific as well as interspecific competition. As the result, the composition of forest stands exhibit progressive or successional changes toward climax formations made up of one or a few shade-tolerant species that are best adapted to the climate and soils of the region (Fig. 10–5). It is believed that the climax formation on fine-textured soils in the northern part the United States consists of hard maple, basswood, yellow birch, and hemlock (Weaver and Clements, 1938). Climax stands on enormous tracts of northern Canada and Siberia, as well as certain portions of high mountains, are composed of spruce species. On plains of central Europe and in the central states of America,

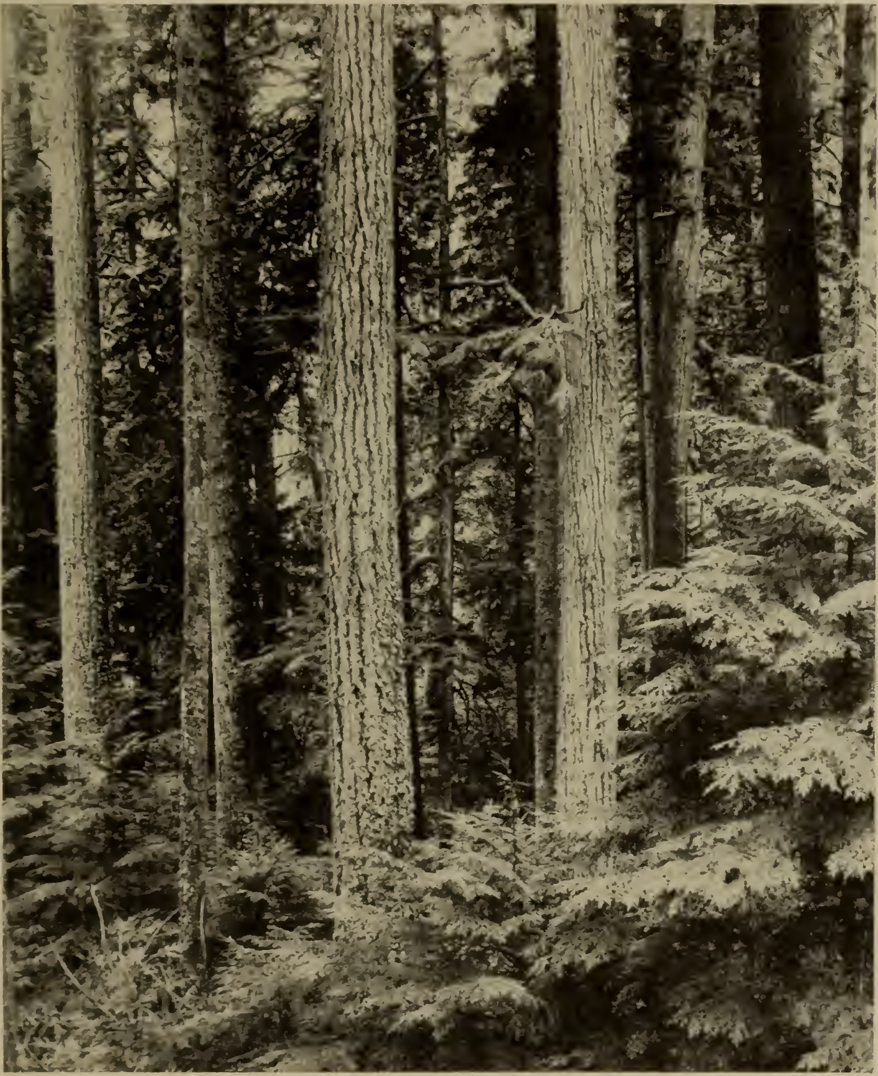


FIG. 10-5. A virgin stand of red fir with an understory of hemlock in the state of Washington—a climax forest. (U. S. Forest Service.)

climax forests include exacting hardwoods, such as beech, maple, and oaks.

The general movement of forest toward the climax is closely related to the gradual changes which take place in the soil profile. Soils are subject to progressive weathering and in the long run tend to increase their colloidal content and water-holding capacity. Concurrently, the xerophytic species of sandy soils are gradually replaced by the mesophytic species. The accumulation of humus and podzolization have a similar effect because both of these processes tend to increase the water-holding capacity of soil.

Obviously, the rate of the two dynamic processes—soil development and crystallization of forest stands—cannot be minutely synchronized. Therefore, soils of the same degree of weathering or genetic development may support forest cover of somewhat different floristic composition. These successional deviations are especially marked on soils of milder environments and diversified topography which present battle grounds of many tree species. Moderately podzolized morainic loams and lacustrine clays are soils whose floristic cover has a particularly high coefficient of variability. The composition of even virgin stands on these soils, transitional between nonpodzolic and podzol lands, includes a melee of white pine, hemlock, white spruce, balsam fir, hard maple, basswood, yellow birch, elms, beech, and red oak. This diversity was effectively catalogued by American woodsmen in a not-too-scientific—but appropriate—term: "hardwood-coniferous type."

Thus, the solution of the problem of soil-forest relationship at times must take into account the dynamic nature of forest stands and consider the variations imposed by successional trends.

Besides the general succession, or a general movement of forest vegetation toward a few climax formations, forest lands often exhibit in their cover radical changes due to local succession initiated through destruction of climax stands by wind storms, fire, or logging (Morozov, 1912; Clements, 1916). The forest cover of deforested lands rarely consists of the species that previously occupied the area. As a rule, logging or fire is followed by the development of temporary stands of shade-intolerant pioneer trees which have low nutrient requirements and can withstand sunscald and frost (Fig. 10–6). Typical pioneer species are scrub oaks, aspen, paper birch, grey birch, pin cherry, jack pine, and Scotch pine. Under favorable climatic conditions, however, some tolerant or semitolerant species, such as Norway spruce, white pine, Douglas fir, and even balsam fir may act as pioneers.

The invasion of pioneer species is governed to a large extent by the composition of the soil. The cut-over areas of calcareous soils are usually occupied by juniper or red cedar, whereas coarse sandy soils are invaded by pines or scrub oaks. Establishment of birch, aspen, and cherries requires soils of a somewhat higher water-holding capacity. Black spruce serves as common pioneer on boreal podzols and alder on swamp grounds.

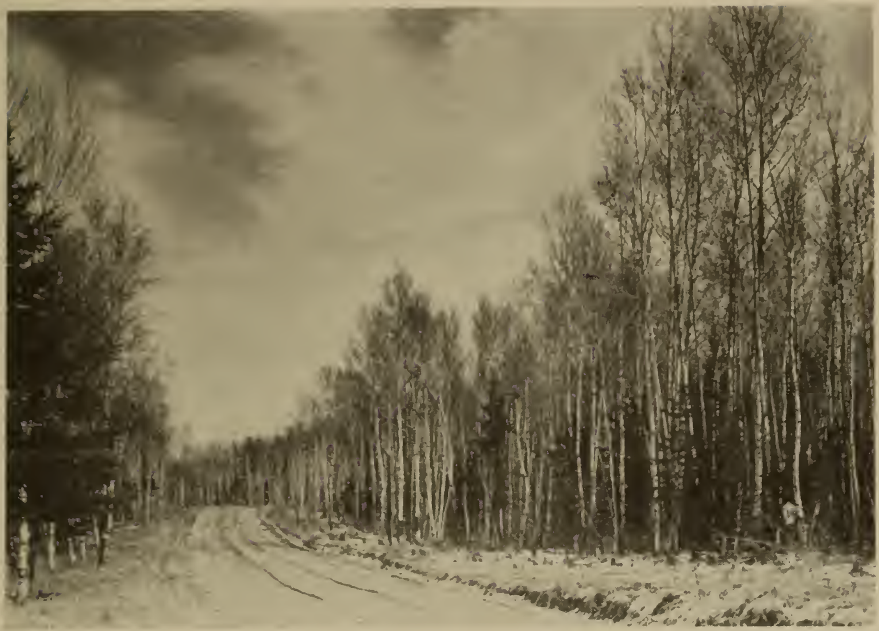


FIG. 10-6. A 35-year-old pioneer stand of paper birch on a podzolized sandy soil of glacial outwash. A reinvasion of tolerant conifers is already in progress. Lake States region. (U. S. Forest Service.)

When a pioneer stand reaches the age of twenty or thirty years, shade-tolerant species, such as spruce, hemlock, hard maple, and yellow birch, establish themselves under the protection of pioneer crowns. In time, tolerant species suppress their guardians by overshading and form a climax forest stand.

The local succession brought on by the destruction or removal of mature forest stands has much greater silvicultural importance than the slow general succession toward climax formations. At times the local succession involves several pronounced links of a successional catena. For example, the entire successional cycle on podzolized sandy loams of the northern United States may be outlined by the following stages: mature hemlock, yellow birch → windfall or fire → aspen, paper birch, pin cherry → pines, red maple, hard maple, basswood → white pine with a hardwood understory → hemlock, hardwoods → hemlock, balsam fir, yellow birch → clear-cut logging → aspen, birch, pin cherry. Similar successional catenas could be drawn for any other soil type. A particularly complicated series of successional changes of the ground cover vegetation is observed in boreal swamp forests of Canada and Eurasia (Huikari, 1952; Wilde, Voigt, and Pierce, 1954).

The continuum pattern of plant distribution. The distribution of a plant species has a tendency to resemble a pattern of shotgun pellets fired at a distant target—a high focal concentration of specimens and a more or less sharp decrease in their density toward the periphery. The frequency of distribution in this pattern is expressed by a parabolic curve commonly encountered in statistics. The peak of the curve usually coincides with the optimum conditions of the habitat; the gradient of the descending sides and the degree of the asymmetry of the curve are determined by the state of site factors

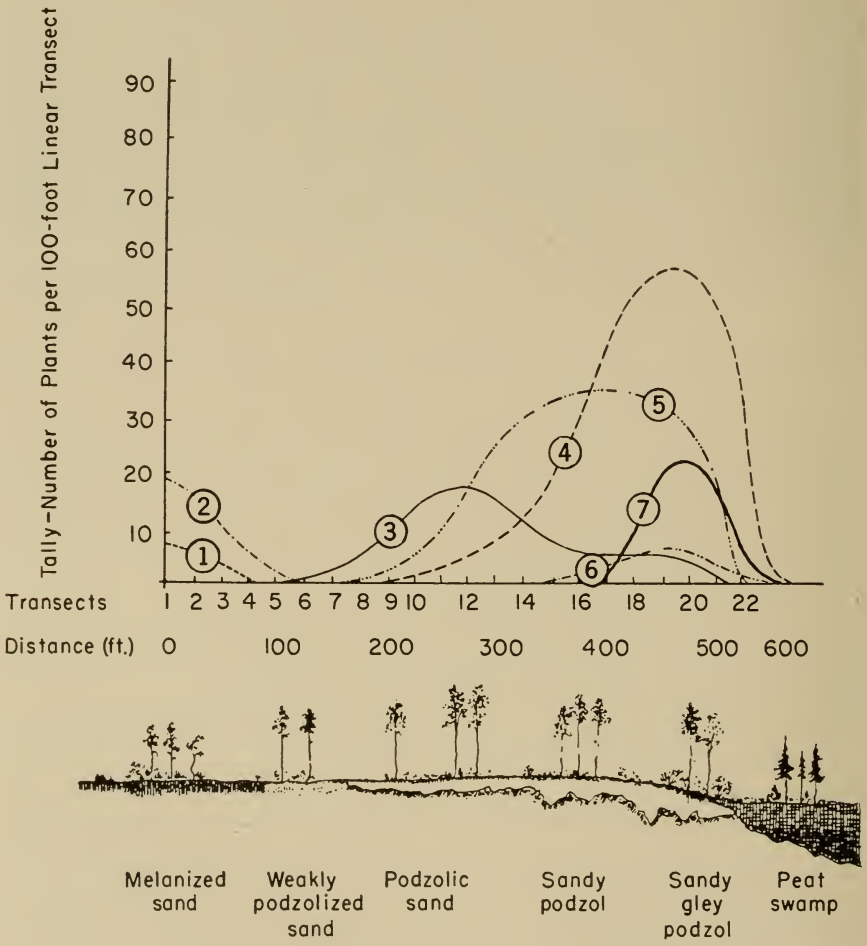


FIG. 10–7. Distribution of several important members of the ground cover vegetation on a melanized sand–sandy gley podzol catena of a glacial outwash in central Wisconsin: (*a*) *Ceanothus ovatus*; (*b*) *Arctostaphylos uva-ursi*; (*c*) *Maianthemum canadense*; (*d*) *Gaylussacia baccata*; (*e*) *Gaultheria procumbens*; (*f*) *Rubus villosus*; (*g*) *Cornus canadensis*. (After Wilde and Leaf, 1955.)

at the margin of the occupied area and the corresponding pressure of competing vegetation.

A determination of the density or frequency of occurrence of different plant species on a sufficiently large area provides diagrammatic results in the form of a series of curves (Fig. 10–7). The relative extent of individual curves serves as an index of the ecological amplitude of corresponding species; the shape of the curves suggests the magnitude of the differences in site conditions encountered on adjacent areas. The steeper the slope of the curve, the greater is the difference in the adjoining habitats, or the greater is their **gradient of ecological heterogeneity.**

A junction of moss peat bog and a gravelly esker is expressed by a steep gradient of the frequency curve for bog-inhabiting species, such as black spruce and tamarack, and a nearly vertical drop of the curve for the esker-supported red pine. Similarly, an abrupt descent of the distribution curve is observed for oak species in the prairie-forest transition of western Minnesota. Contrariwise, a contact of northern moraines with glacial outwash usually is registered by gentle slopes of the distribution curves for either spruce or pine species. The segment produced by the intersection of the two curves delineates the ecotone or the tension zone of the mixed pine-spruce forest; it also indicates the ecological efficiency of the morainic shoulder underlying outwash sand (Fig. 10–8). A broad zone of the prairie-forest transition of southern Russia is another example of a gentle frequency curve for oak species.

The concept of the gradient of ecological heterogeneity is applicable to broad geographic zones as well as forest communities found on small areas of rolling topography or diversified soil conditions, to trees as well as ground-cover plants. The knowledge of the gradient for certain species often helps in the detection of ecologically important variations in soil conditions.

The parabolic pattern of plant distribution was recently identified with the **continuum** (Curtis and McIntosh, 1951), a concept implying a gradual change in which "a fundamental common character is discernible." From a practical standpoint the idea of continuum annihilates or at least weakens the rigid framework of soil-forest units which often placed forest types into artificial pigeonholes. In a broad meaning of the term, continuum involves the fourth dimension and, hence, embraces the space-time changes toward climax formations. In the light of this definition the relationship between soil and vegetation implicates not only the existing forest cover but the entire successional catena of pioneer, preclimax, climax, and postclimax types. As has been pointed out, the knowledge of the

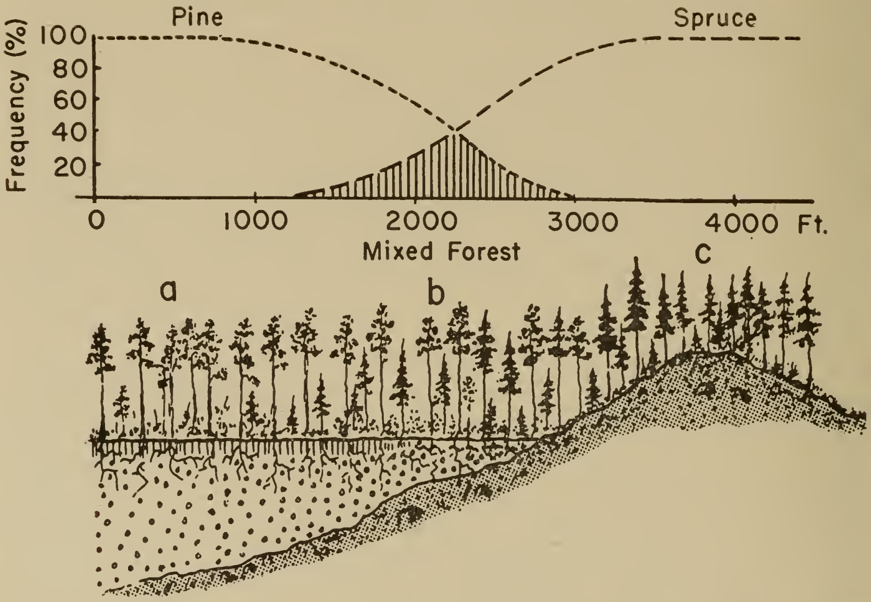


Fig. 10–8. Distribution of pine and spruce as influenced by morainic shoulder underlying sandy outwash: (*a*) region of pure pine forest; (*b*) region of mixed pine-spruce stands; (*c*) region of pure spruce forest.

entire successional cycle is important for the success of both artificial reforestation and silvicultural cuttings.

Ecological relations and principle of relativity. The cavalcade of ideas that crossed the field of plant ecology during the past half century has brought down many artificial barriers and opened several new trails. This is particularly true in regard to the interdependence of soil and forest growth. In this sector of natural philosophy the rigid framework was replaced by flexible patterns, the absolute values by statistical means or medians, the static concepts by dynamic concepts, and peephole views of particular details by a broad vision of integrated landscapes.

Today the relationship of soil and forest growth, not unlike modern physics, is anchored in the law of probability, in its own theory of relativity, and in the principle of uncertainty. Only on the realistic foundation of these modern concepts, underlying the structure of both macrocosmos and microcosmos, can the theory of soil-forest types escape the falsehood of unqualified generalizations, speculative classificational schemes, and arbitrary labels.

The problem of the relation of soils and forest growth is not a difficult one, but it can be solved only within certain climatic coordinates and by taking into account the dynamic changes of both soil profile and forest vegetation. Furthermore, its solution requires a consideration of the entire regional soil-forest landscape, careful analysis of soils, and the determination of floristic, mensurational, and wood-utilizational characteristics of forest cover. These are the prerequisites which permit the synthesis of analytical data and the delineation of a limited number of soil-forest units providing a sound foundation for silvicultural management.

SOIL-FOREST TYPES IN DIFFERENT CLIMATIC ZONES OF THE PLAINS AND MOUNTAINS

The following descriptions of different forest regions were chosen to illustrate by concrete examples the link that exists between soil and forest cover, its composition, rate of growth, capacity for natural regeneration, quality of wood, and stability against adverse factors. These outlines are largely confined to large soil groups of major silvicultural importance, namely, podzols, melanized soils or brown-earths, prairie-forest soils, and soils of the mountains. In order to demonstrate the universal validity of the basic relationships, the descriptions of American soil-forest units are paralleled by the descriptions of units located in fairly comparable climatic regions of Europe and Asia.

BOREAL FORESTS OF KARELIA; FENNO-SCANDIAN SHIELD

> *The long road through the moors, and up into the forest . . . the road through the great Almenning—the common tracts without an owner; no man's land.*
>
> —Hamsun, *Growth of the Soil*

There is more than one reason why a review of soil-forest units encountered in different parts of the world should begin with the boreal or "taiga" forests bordering the treeless mosaic of bogs, heaths, and meadows, collectively called "tundra."

The environment of the far north, with its brief growing season and low average temperature, permits the existence of comparatively few microthermic species and tends to level off the growth effect of the less-prominent differences in the composition of soils. The resulting simplicity of the ecological structure greatly facilitates the insight into the relationships between the soil and forest vegetation—relationships which are often obscured by the floristic and pedological complexities of forest stands in milder climates.

The taiga forests form a circumpolar belt which includes the northern parts of Alaska, Canada, Fenno-Scandia, Northern Russia, and Siberia. This unique geographic position has facilitated investigations of the boreal soils and vegetation by scientists of many tongues and classificational approaches. Besides the magnetic pole, the boreal environment appears to have some other attractions which have driven many foresters and students of nature to forego the bustle of civilization for the solitude and silence of the north. During the last three decades the search of knowledge for knowledge's sake has been replaced by organized investigations motivated by geopolitical and strategic interests. These surveys have brought into existence a large volume of literature on the ecology of "no man's land." Because of extremely short summer periods, the work of foresters in boreal regions at times could compete in hardships with polar expeditions (Fig. 10–9).

Fig. 10–9. Winter working conditions in the region of boreal forest of Karelia.

Although northern forests of Europe, Asia, and America comprise different species of trees and some different species of ground-cover plants, they maintain the same pedogenetic and ecological pattern. Essentially, the floristic landscapes of the three continents present different orchestrations of the same boreal symphony in which the theme of Scotch pine is assigned to cembra pine, jack pine, or black spruce; the theme of Siberian larch to tamarack, and so on. Throughout the entire taiga zone the distribution of forest types is influenced largely by the lay of the land and the position of the ground water table, the degree of weathering of parent materials, the proximity of the ever frozen substratum or the "permafrost," effect of inundation, and the occurrence of deposits high in carbonates. Detailed descriptions of boreal soils and forests are incorporated in recently published English-language works of Kujala (1945), Marr (1948), Hustich (1949), Cajander (1949), Tamm (1950), Kellogg and Nygard (1951), Huikari (1952), Wilde *et al.* (1954), Linteau (1955), Siren (1955), and Place (1955).

The selection of the Karelian boreal forest was made because this territory was subjected to floristic as well as pedological appraisal by the Finnish and Russian foresters. The combination of these two approaches has definite advantages: it eliminates the pitfalls encountered in both the abstract soil classifications and in the scrupulous adherence to the arbitrary floristic labels. The description of the principal soil-forest units was compiled on the basis of papers by Cajander (1949), Sukachev (1928), Ilvessalo (1923), Morozov (1930), and Leaf (1956).

Soils of rock outcrops and skeletal substrata. In the severe boreal environment, which is hostile to forests, outcrops of rocks, boulder pavements, gravelly eskers, and other regolithic deposits present natural forts which protect trees from the invasion of *Sphagnum* mosses and their allies. Scotch pine, Norway spruce, birch, and juniper maintain their foothold on these inhospitable grounds largely because of the amazing ability of their root systems to clasp barren surfaces and penetrate crevices. Even after the trees are blown down by the wind, they often continue to grow, the branches forming the upright stems.

The ground cover consists predominantly of lichens, *Hypnum* mosses, and *Vaccinium* low shrubs; the remains of these plants together with tree litter form a peatlike layer which at times rests on unweathered substratum and can be easily removed in large sheets. The rock outcrops are often completely dressed in a white blanket of *Cladonia* lichens and on purely floristic basis are identical with coarse sandy soils.

In the milder parts of the region the yields of forest stands on skeletal soils vary between six and ten cords per acre. Near the timber line, however, trees are but a few feet tall, and their occurrence is confined to the warmer southern and western exposures of outcrops and mounds.

Lean sands; Yag type; Cladonia type or Pinetum cladinosum. Coarse sandy soils derived largely from quartz occupy island-like areas of sand dunes and narrow strips bordering rivers. The soil profile consists of lichen crust mor and a weakly developed endorganic horizon; at times the soil is touched by the process of podzolization and has a strongly acid reaction.

The virgin as well as second-growth stands are composed of Scotch pine varying in density from 40 to 60 per cent of the full stocking; the average height seldom exceeds 50 feet, and the yields average 10 cords per acre. Because of the poor form of stems, the wood is used largely for distillation. The stands on these sites are frequently destroyed by fires, for the low-hanging branches of pines facilitate the spread of ground fires to the crowns.

These sites are classified as *Cladonia* type, a highly appropriate designation, for their surface has a snowlike appearance imparted by different species of lichens: *Cladonia alpestris, C. silvatica,* and *C. rangiferina,* the "reindeer moss." *Arctostaphylos uva-ursi, Vaccinium vitis-idaea,* and *Empetrum nigrum* are occasional associates of the lichens.

Podzolic sandy soils; Moss-Yag type; Vaccinium type or Pinetum vacciniosum. The influence of the textural composition of soil on the growth of boreal forests is considerably diminished by the effects of podzolization—the accumulation of raw organic remains and the development of slowly permeable *B* horizons. By and large, however, moderately podzolized soils of a coarse texture support stands of Scotch pine with some birch, aspen, juniper, and struggling Norway spruce. The density of stands varies between 50 and 70 per cent, but the logs have a good form and the yield may be as high as 15 Mbf per acre. The total volume of virgin stands in boreal regions, however, is not always indicative of the current increment of the stand, for Scotch pine in northern Finland is managed on rotation of 250 years and even higher.

The ground cover is made up of *Vaccinium vitis-idaea, Arctostaphylos uva-ursi, Empetrum nigrum, Calluna vulgaris, Linnaea borealis, Ledum palustre,* and *Andromeda polifolia.* The cover of mosses consists largely of *Hylocomium proliferum* and *Pleurozium Schreberi.* Some foresters consider this site as a component part of the *Pinetum hylocomiosum.* The *Vaccinium* and *Cladonia* types are often connected by a transition, *Empetrum* type, characterized by a predominance of crowberries. Figure 10–10 indicates schematically the influence of topography and soils on the distribution of floristic forest types recognized by Finnish foresters. Severe fires often convert the *Vaccinium* type into a temporary *Calluna* type.

Podzolized sandy loams; Soo-Bor; Myrtillus type or Pinetum myrtillosum. This designation implies a series of "ecologically equivalent" sandy soils whose water supply is increased by pronounced podzolization, a fairly high content of mineral colloids, proximity of the morainic substrata, or the presence of a deep gley horizon. Either

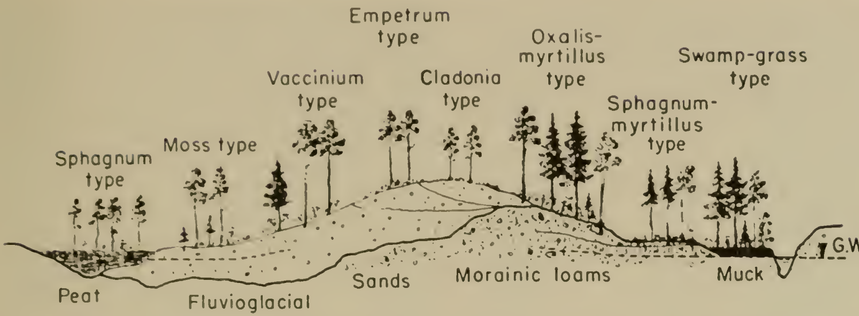


FIG. 10–10. Distribution of floristic forest types in relation to soils and topography in northern Finland (a generalized scheme).

of these features accelerates the rate of pine growth and permits participation of spruce and birch in the main story. The pine reaches an average height of 80 feet and contributes a larger share toward the yield of about 25 Mbf per acre at the age of 100 years. The understory is formed by spruce, juniper, and willows.

The ground vegetation is dominated by *Viccinium myrtillus*; the prominant associates include *V. vitis-idaea, Pyrola secunda, Geranium silvaticum, Maianthemum bifolium, Linnaea borealis,* and *Deschampsia flexuosa.* A nearly continuous carpet of mosses is made up of *Pleurozium, Hylocomium,* and *Polytrichum commune.* Soils of this group have a rather high productive potential, which often permits a replacement of Scotch pine by Norway spruce. A similar relationship exists between white pine and hemlock on unassorted sandy deposits of the United States and Canada. Pioneer stands are usually composed of birch (Fig. 10–11).

Gley-podzolic sandy soils; Kercha Yag; Moss type or Pinetum ledosum. This type is confined to gentle slopes of glacial deposits and plateaus of the river divides. The soil profile consists of a peat-like saprogenous mor or bog mor which is often underlain by a dark, 6-to-8 inch-thick horizon with infiltrated humates; the *B* horizon rests on a water-logged gley layer of sandy texture. The slowly growing stands of Scotch pine are of a striking appearance because of the beardlike lichens, *Usnea barbata,* hanging from the branches. The occurrence of spruce, aspen, and birch now and then breaks the depressing monotony of this type. Bog birch and willows form a scanty understory.

The ground is covered by a solid blanket of mosses of *Hylocomium, Pleurozium, Polytrichum,* and *Sphagnum* genera; other members of the association include *Ledum palustre, Vaccinium ulliginosum, V. myrtillus, V. vitis-idaea, Carex globularis,* and *Rubus chamaemorus.*

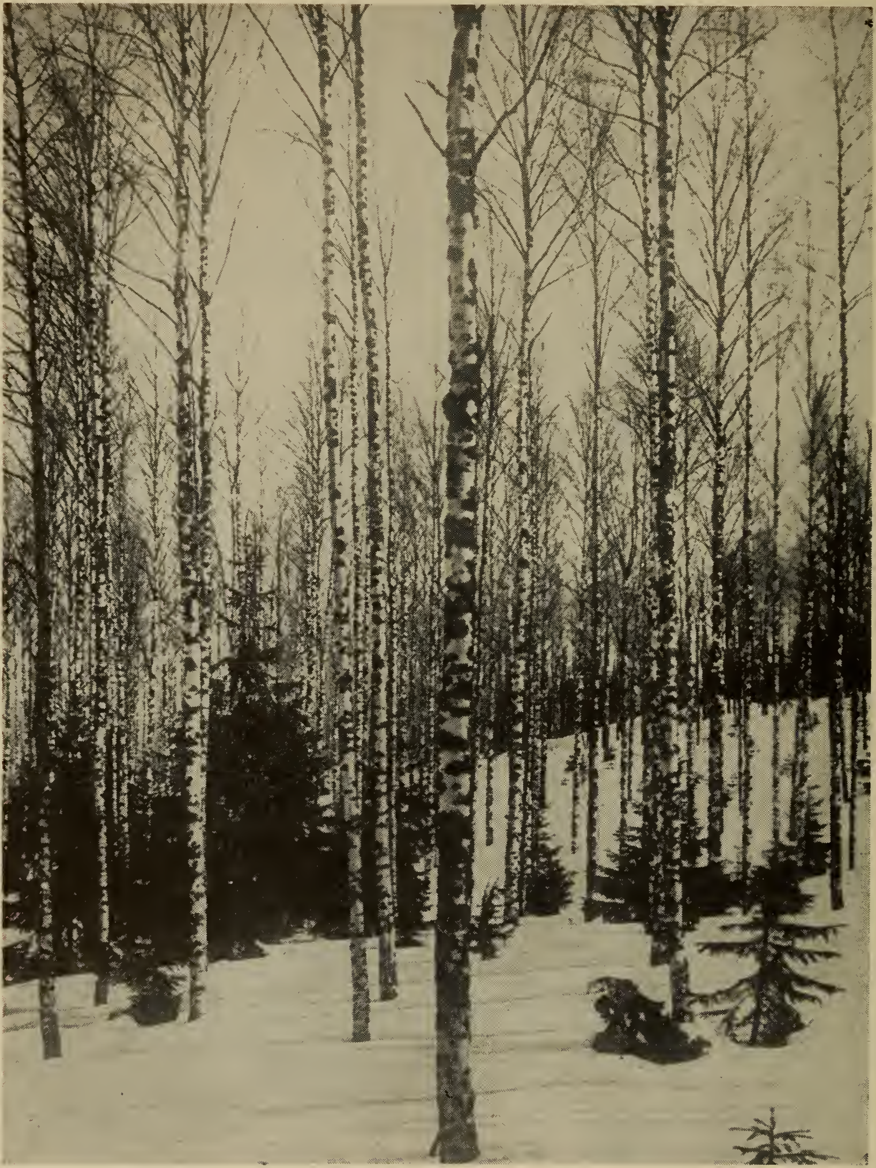


Fig. 10–11. Pioneer stand of birch with understory of spruce established on a burned-over area in Finland. (Forest Research Institute of Finland.)

Moss peat bogs; Niur type; Sphagnum type or Pinetum sphagnosum. An increase in the thickness of the moss-peat layer leads to the development of an oligotrophic or nutrient-impoverished swamp. Such swamps may be formed on either sandy or a "blue clay" substrata. The principal peat-forming constituents in advanced stages of succession are: *Sphagnum fuscum, S. papillosum, Polytrichum strictum, Cassandra calyculata, Ledum palustre, Eriophorum vaginatum, Andromeda polifolia, Carex* spp., and *Scheuzeria palustris.* The open stands of Scotch pine exhibit large percentages of dead trees and trees with "dry tops"; the maximum height is 15 feet, and the volume seldom exceeds 5 cords per acre.

Because of the geological youthfulness of the region, oligotrophic peat deposits have comparatively limited distribution; in many instances the irreversible fixation of nutrients by *Sphagnum* tissues is counteracted by nutrient-enriched remains of sedges encountered at a depth of 1 or 2 feet. This is not always true in the southern parts of the Fenno-Scandian shield, where, in the opinion of some Finnish foresters, the *Sphagnum* to be good must be not only dead but also cremated.

Podzolized loams; Ramen or Kholm type; Oxalis-Myrtillus type or Piceetum oxalidosum. Soils of this designation are usually of morainic origin, but they may be derived from a great variety of other parent material enriched in nutrients and providing an adequate water-holding capacity, permeability, and aeration. The ectorganic layer of friable consistency seldom exceeds a thickness of 2 inches and usually rests on a horizon with incorporated humus. The intensity of podzolization varies within wide limits. In some instances the soil is underlain by a deep gley horizon. On substrata of limestone, gypsum, calcareous shales and glacial tills, soils acquire morphology of "boreal mulls" (Tkachenko, 1911) or "dark podzolic soils" (Filatov, 1945).

Forest stands are composed largely of spruce with some pine, birch, and aspen; the understory includes juniper, mountain ash, wild rose, raspberry, and mezereon. The trees reach a height of nearly 90 feet; the wood is of excellent quality and free from heart rot. These are the most productive stands of the north, yielding as much as 30 Mbf per acre. In higher latitudes, however, the volumes per acre are decreasing because of the low density of stands (Fig. 10–12).

The ground cover includes *Oxalis acetosella, Mainanthemum bifolium, Vaccinium myrtillus, Rubus saxatilis, Lycopodium annotinum, Geranium silvaticum, Vicia silvatica, Orobus vernus, Pyrola secunda, Equisetum silvaticum, Trientalis europea, Dryopteris phegopteris, Carex digitata,* and *Lusula pilosa.* The absence of mosses, except some *Hylocomium,* is a conspicuous feature.

Alluvial soils; Log type, Grass type or Piceetum herbosum. The stream-bottom deposits support stands of spruce with some birch

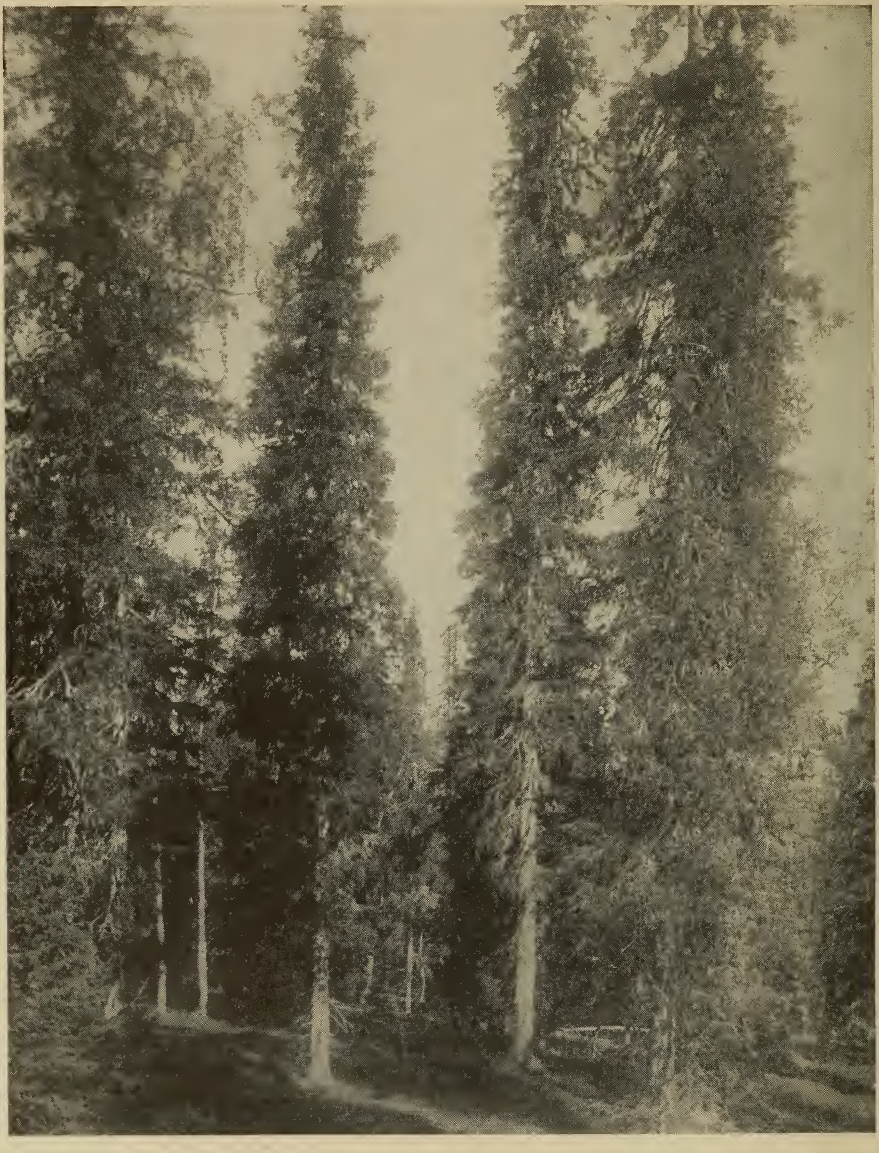


Fig. 10-12. Spruce forest of Finland. (Forest Research Institute of Finland.)

and the understory of alder, mountain ash, cherry, and willows. These stands are distinguished by a rich ground cover of herbs, including *Dryopteris phegopteris, Equisetum silvaticum, Carex globularis, Trientalis europea, Ranunculus lapponicus, Comarum palustre, Coralliorhiza innata,* and *Rubus chamaemorus.* The sporadic occurrence of mosses, including *Sphagnum*, and the scarcity of heath shrubs are characteristic. The dense stands of spruce and birch attain an average height of 70 feet, and the yields exceed 30 cords per acre.

Alluvial soils carry forest cover far into the tundra region, but in high latitudes stands are replaced by dwarf willows.

Gley-podzolic loams; Rovniad type; Myrtillus-Sphagnum type or Piceetum myrtilloso-sphagnosum. This type occupies extensive flats of fine-textured soils lacking internal as well as surface drainage. The soil profile consists of a saprogenous, peatlike mor humus, attaining a thickness of 7 inches, and a leached horizon stained with humate suspensions; the partly mottled BG layer at times grades into the permafrost. The surface soil remains free from ice only during the brief growing season. The rugged microrelief testifies to frequent windfalls. The slowly growing stands of Norway spruce include some sprouts of birch, bog birch, and mountain ash. The heights of dominant trees do not exceed 45 feet, and the yields vary between 4 and 7 cords per acre. Half of the stand is usually infested with heart-rot fungi. After fire, this type becomes a waste land, and it is ten to fifteen years before the clumps of brushy birch, willows, and mountain ash begin to appear.

The ground-cover vegetation consists of *Sphagnum amblyphollium*, *S. Russovii*, *Polytrichum*, other mosses, *Vaccinium myrtillus*, *V. ulliginosum*, *Equisetum silvaticum*, *Carex* spp., *Cassandra calyculata*, *Rubus chamaemorus*, and *Empetrum nigrum*.

With further deterioration of drainage the area is taken over by mosses and sedges and converted into "sogra" type or *Piceetum caricetosum*, a land of sedge hummocks, emerging from standing water. On these habitats a few dozen spruce per acre are fighting a loosing battle for existence.

SOIL-FOREST TYPES IN THE PODZOL BELT OF THE GREAT LAKES REGION OF AMERICA

> *From the great lakes of the Northland*
> *From the mountains, moors, and fenlands*
> *Where the heron, the Shuh-shuh-gah,*
> *Feeds among the reeds and rushes. . . .*
> —Longfellow, *The Song of Hiawatha*

No other part of the podzol zone of the world exhibits the diversity of soil and floristic conditions that is found in the northern parts of Minnesota, Wisconsin, and Michigan. This diversity is a result of certain peculiarities of climate, variegated geologic substratum, caprices of glaciation, and richness of American flora.

In spite of the fact that the described section of America produces podzols whose exterior features could win a pedigree prize in any world contest, this end result is achieved by a combination of climatic influences essentially different from that in the other parts of the podzol zone. Like all their relatives, soils of the Hiawatha country rest during the long winter under a deep blanket of snow, but they receive special radiation and hydrothermal treatment during the growing season. Summertime in the podzol zone of Eurasia is marked by comparatively low temperatures and prolonged drizzling rains—a state of climatic factors conducive to the toothache and the outlook of Chekhov's characters. The summer in the Land o' Lakes abounds in sunshine, high day temperatures, and infrequent but heavy rainfall. This difference in the arrangement of climatic influences brings to the same pedological quotient—podzol soils—the areas of Eurasia receiving less than 20 inches of precipitation and the areas of North America with a precipitation exceeding 30 inches.

This similarity in the development of soils, however, is not extended to conditions of forest growth regulated by the duration of photosynthetic activity and the rate of transpiration. The yields of 120 Mbf per acre, or about 1,700 solid cubic meters per hectare, produced by virgin stands of white pine in the Lake States, can hardly be visualized by foresters working in the podzol zone of Eurasia, where a volume of 600 cubic meters per hectare is a rare exception.

The geological substratum of the region is formed by representatives of all important groups of rocks: siliceous, feldspathic, ferromagnesian, and calcareous. Different aspects of the glaciation left their imprints in the surface geology of the region. Extensive table-like plains of glacial outwash and lacustrine deposits are interrupted by the rugged ridges of terminal and recessional moraines, plateaus of ground moraines, corrugated "sheep backs," winding "snake mounds" of eskers, wavelike aeolian sands, and drumlins resembling half-submerged whales. This melee of land forms is ornamented by thousands of lakes, the last manifestation of the vanished glaciers. Many rivers and streams serve as pulsating arteries of the three-state body of the land.

Forests of the Great Lakes include nearly all tree genera of Europe and northern Asia and most of the temperate zone genera found in North America. The same just about holds true in regard to shrubs and ground-cover vegetation. At times the floristic composition of forests in the Lake States closely resembles that of forests in Scot-

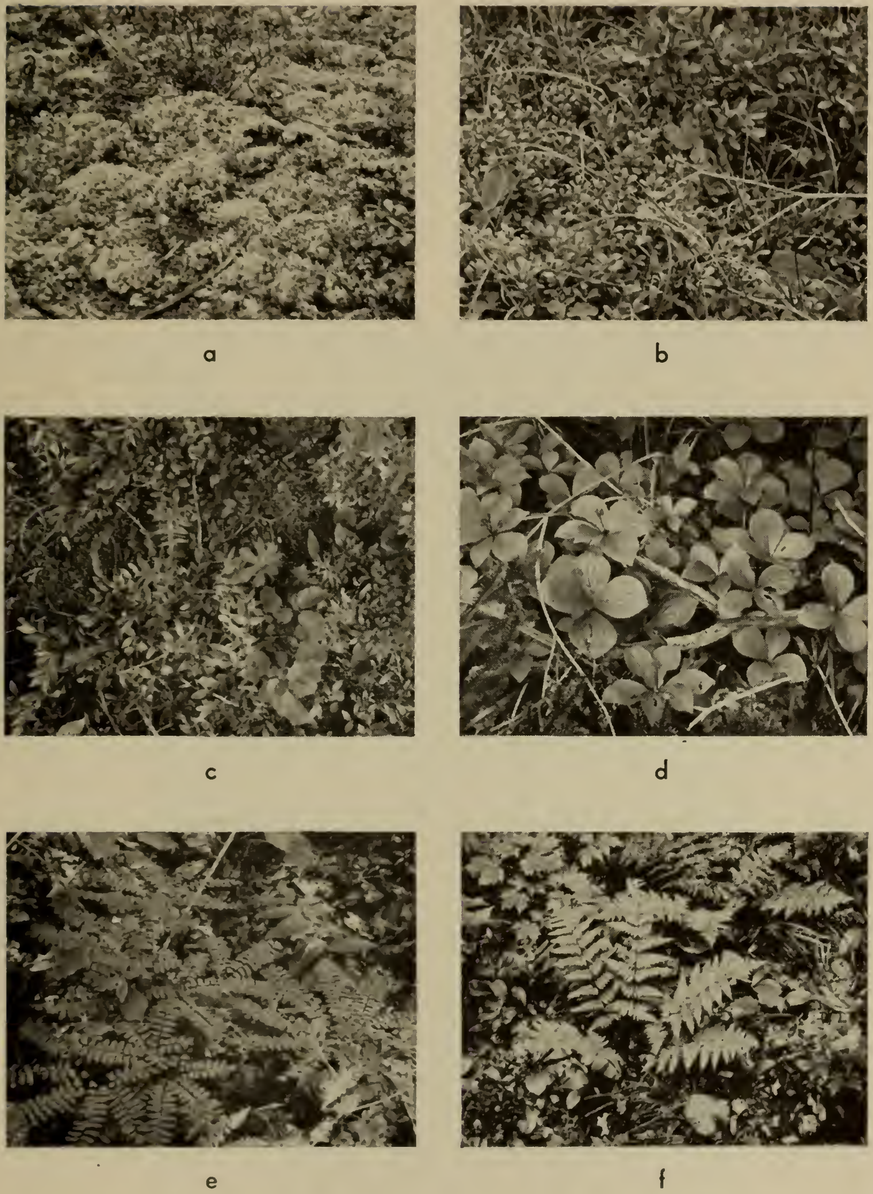


Fig. 10-13. Examples of characteristic ground cover associations of the Great Lakes forests. (*a*) *Cladonia* type of aeolian sands; (*b*) *Arctostaphylos-Ceanothus* type of melanized sands; (*c*) *Vaccinium-Maianthemum-Gaultheria* type of podzolized sandy soils; (*d*) *Cornus-Lycopodium* type of hardpan podzols; (*e*) *Adiantum-Osmorhiza-Thalictrum* type of melanized loams; (*f*) *Galium-Carex-Fern* type of gley-podzolic loams.

land, Fenno-Scandia, or Manchuria (Wilde, 1932). Figure 10–13 presents samples of ground-cover associations characteristic of different soils (Wilde and Lafond, 1954).

In a broad outline the soils of the northern part of the Lake States may be combined into three large genetical groups: melanized soils, podzolized soils, and swamp or organic soils. Soils of uplands and swamps are connected by catinas of hydromorphic gley soils. Figure 10–14 describes the most important soil-forest units.

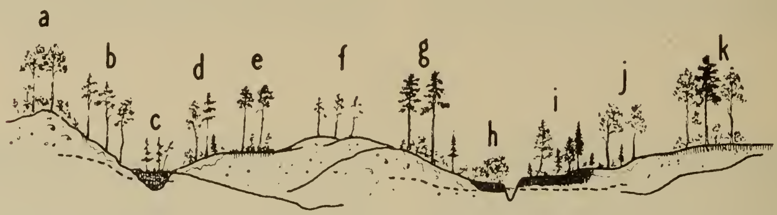


Fig. 10–14. A schematic outline of the soil-forest units in the podzol zone of the Lake States region: (*a*) melanized morainic loam—hard maple, basswood; (*b*) podzolized morainic loam—hemlock, yellow birch; (*c*) moss peat—black spruce, tamarack; (*d*) gley-podzolic sand—pines, paper birch, aspen; (*e*) melanized outwash sand—red pine; (*f*) aeolian sand—jack pine; (*g*) podzolized gravelly sandy loam—white pine; (*h*) alluvial muck—tag alder; (*i*) woody peat—white cedar, balsam fir, spruces; (*j*) gley-podzolic loam—black ash, white elm, red maple, balsam fir; (*k*) melanized outwash silt loam—hard maple, basswood, white pine.

Melanized sands; Arctostaphylos-Ceanothus type. These coarse sands, resembling prairie soils, occupy extensive level or undulating plains of fluvioglacial deposits. Their virgin forest consists predominantly of red pine with incidental admixtures of jack pine and different "scrub oaks"—black oak, burr oak, and hybrides of the red oak group. The sporadic understory of shrubs comprises *Corylus americana, Prunus pumila, Salix humilis,* and *Rosa* spp. The association of lesser plants is remarkable in the constancy of its composition; it includes *Arctostaphylos uva-ursi, Ceanothus ovatus, Vaccinium angustifolium, Fragaria virginiana, Lycopodium complanatum, Panicum depauperatum, Koeleria cristata, Danthonia spicata,* and other xerophytic grasses.

Pioneer stands, usually of postfire origin, are composed of jack pine. Since the high temperature of fire hastens the opening of jack pine cones, reproduction often exceeds 40,000 seedlings per acre. This generosity of nature eventually requires expensive elimination on nonmerchantable material from the crowded stagnating stands. A destruction of immature reproduction of pines by fire is followed by invasion of oak sprouts—the last recourse of the forest in its fight against herbaceous vegetation.

Stands of red pine provide sound and well-formed timber (Fig. 10–15). The yields approach 25 Mbf per acre at the age of one hundred years. Pioneer stands of jack pine average between 10 and 15 cords per acre at the age of forty years (Wilde, Paul, and Mikola, 1951). Melanized sands are sought by private enterprise because of their gentle topography, passability of roads, freedom from stones, and suitability of land to mechanized tree-planting and production of pulpwood on short rotations.

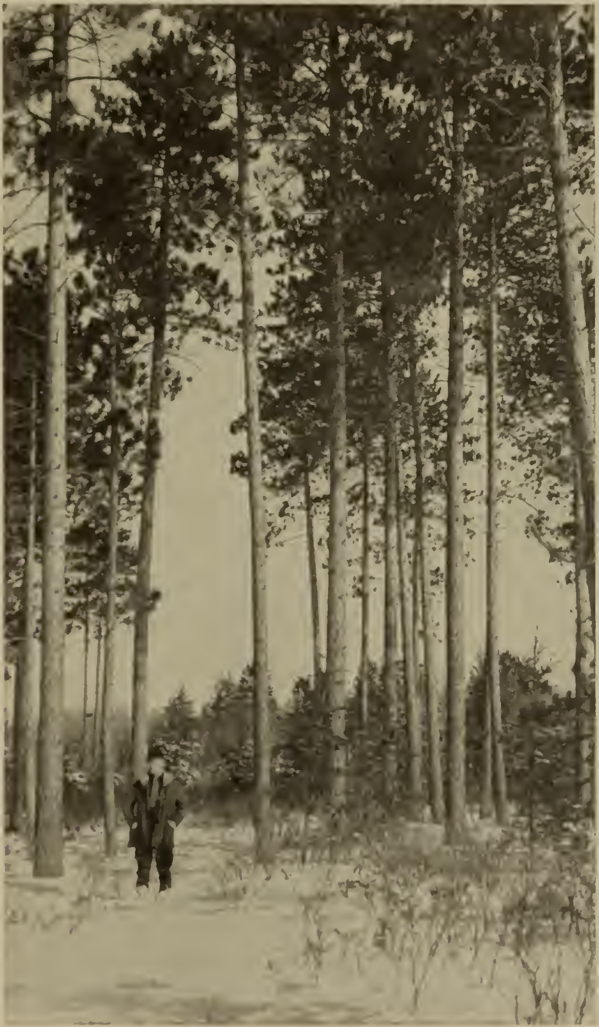


Fig. 10–15. Mature stand of red pine on melanized sand of glacial outwash, *Arctostaphylos-Ceanothus* type.

Melanized loams; Adiantum-Osmorhiza-Thalictrum type. These soils, similar to the so-called "weakly podzolized" or "mull" soils of Europe, occupy loesslike outwash plains and elevated flat portions of moraines. At times they are found on substrata enriched in lime or ferromagnesian minerals or underlain by a hard ground water. The humus layer is usually microbiotic mull in upland soils and earthworm mull in subirrigated soils. The profile may totally lack signs of podzolization or may exhibit faintly outlined A_2 and B horizons.

The climax forest is dominated by hard maple; its common associates are basswood, elms, red oak, hornbeam, hackberry, red maple, and black cherry. In some localities stands have an intrusion of white ash, beech, and white pine. *Dirca palustris* and species of *Viburnum, Sambucus,* and *Rubus* are the common members of the shrub understory. The ground-cover association includes *Adiantum pedatum, Osmorhiza claytoni, O. longistylis, Actaea rubra, Thalictrum dioicum, Dicentra cucullaria, Anemonella thalictroides, Aralia nudicaulis,* and *Smilax hispida.*

Hardwoods have a remarkable stability on melanized loams. Even after a removal of stands by logging or fire, the area is regenerated by sprouts and seedlings of deciduous species. Invasion of pioneer trees, particularly aspen, takes place only after repeated fires have completely suppressed the regenerative capacity of hardwoods. The antagonistic behavior of the climax hardwoods is especially pronounced when attempts are made to introduce artificially more valuable conifers, such as spruce. The underplanted seedlings are then exposed to the onslaught of the entire hardwood community including trees, ground-cover plants, browsing animals, and parasitic organisms.

The yields of virgin hardwood stands vary between 12 and 18 Mbf per acre.

Melanized gley loams; Sanguinaria-Arisaema type. The hydromorphic phases of melanized loams are characterized by an especially deep layer of crumb mull humus inhabited by large *Lumbricus* earthworms. The mottling of reduced oxides is usually encountered at a depth from 2 to 3 feet manifesting the development of a gley substratum.

The forest cover of hardwoods has a high percentage of slippery elm and rock elm and occasionally includes yellow birch and black ash. The ground vegetation of mull plants is interspersed with species of high water requirements, such as *Arisaema atrorubens, Sanguinaria canadensis, Trillium grandiflorum, Allium tricoccum,* *Impatiens biflora, Galium triflorum, Carex intumescens,* other sedges, and numerous ferns.

Melanized gley loams belong to soil types paradoxical with respect to their productive capacity. In spite of the apparent richness of the soil, indicated by its "fat" layer of mull humus, and the abundance of moisture, hardwood stands show a moderate increment, poor form, and premature deterioration (Fig. 10–16). A few stems of white

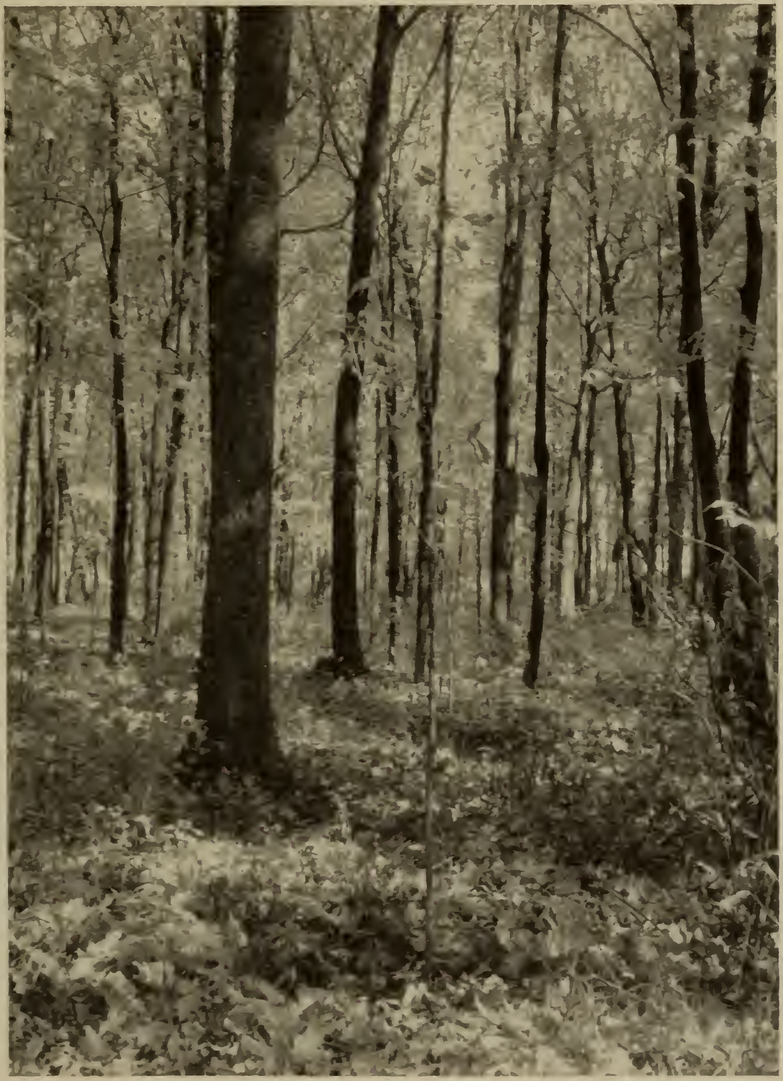


Fig. 10–16. Second-growth stand of hard maple, red oak, and white elm on melanized gley silt loam, *Sanguinaria-Arisaema* type.

pine, however, may raise the total yield of the stand to nearly 20 Mbf per acre, but this species has only limited distribution on melanized gley loams; a high percentage of white pine leads to a gradual destruction of the mull layer and the development of gley-podzolic soil.

Sandy podzols; Gautheria-Vaccinium-Cornus type. Strongly podzolized sandy soils, with their substantial layer of lignomycelial mor and indurated *B* horizon, present close similarity with their morphological relatives of Europe. However, contrary to European experiences, American podzols are neither sick nor unproductive soils. Even the extremely leached varieties with a 3-foot-thick, rock-like hardpan at times support stands of white pine yielding up to 30 Mbf per acre. It appears, therefore, that the deterioration of forest stands on podzols of Germany and other European countries is caused by biological or nutritional deficiencies rather than by the mere physical influences of the Ortstein horizon.

The virgin forest cover on podzolized sandy soils consists largely of white pine with some balsam fir, white spruce, black spruce, and red pine (Fig. 10–17). The ground cover is characterized by the presence of *Gaultheria procumbens, Vaccinium myrtilloides, Maianthemum canadense, Pteridium latiusculum, Trientalis borealis, Chimaphila umbellata, Epigaea repens, Cornus canadensis, Linnaea borealis,* and *Lycopodium* spp.

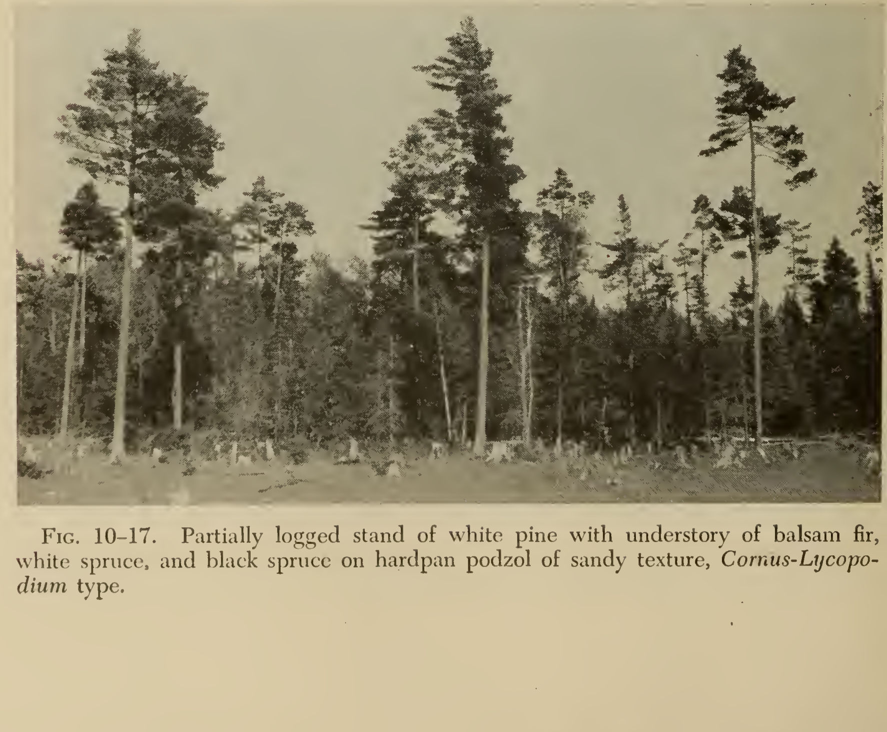


FIG. 10–17. Partially logged stand of white pine with understory of balsam fir, white spruce, and black spruce on hardpan podzol of sandy texture, *Cornus-Lycopodium* type.

Pioneer stands are formed largely by trembling aspen, and in some instances large-toothed aspen, paper birch, and red maple. Within a few years after pioneer stands close canopy, they are infiltrated by fir, spruce, and pines. In spite of all man's mishandling, the second-growth stands on podzolized sandy soils present, in their stability and beauty, the incarnation of most ambitious silvicultural dreams. Very likely, the high productive potential and regenerative capacity of these soils rest in their ability to store water in the colloid-enriched *B* layer.

In exceptional cases, the yields of virgin white pine on moderately podzolized sandy soils exceed 100 Mbf per acre. The pioneer stands of aspen produce as much as 40 cords per acre at the age of about forty-five years.

Podzol loams; Clintonia-Lycopodium type. This soil and its forest cover present the climax formation of the region. Depending upon the percentage of sand particles, soil profiles exhibit either strongly cemented or compacted and mottled accumulative horizons. The thick, lignified raw humus at times is replaced by a thin and friable branlike mor harboring arthropods.

The forest cover consists of hemlock with some yellow birch, balsam fir, and poor hard maple. Stands have no understory of shrubs except for occasional *Taxus canadensis.* The ground cover includes *Clintonia borealis, Lycopodium* spp., *Cornus canadensis, Mitchella repens, Maianthemum canadense, Coptis trifolia, Linnaea borealis*, and *Monotropa uniflora.*

The milieu of mature hemlock stands is distinguished by solitude and silence. This highly exclusive forest community is the result of the agelong struggle which finally eliminated exacting hardwoods, shrubs, and many feather- and fur-clad associates. Unfortunately, the victor in the conflict, the hemlock, is inferior in rate of growth and quality of wood to its vanquished rivals. It produces only a modest volume of some 12 Mbf per acre of second-grade lumber (Fig. 10–18). Sooner or later the shallow anchored hemlock stand is uprooted by wind or turned into ashes by a stroke of lightning. Then the ash-fertilized or wind-replowed soil accepts weeds and pioneer broadleaved trees which rejuvenate soil for a new long series of alternating conquests and subjugations.

Calcareous podzols. Calcareous podzols, or so-called "gray wooded soils," are confined to lime-bearing glacial and lacustrine deposits. The morphology of these soils includes a thick, nearly neutral layer of matted mycelial mor, light gray slightly acid to alkaline leached layer, and a grayish-brown, blocky *B* horizon which rests

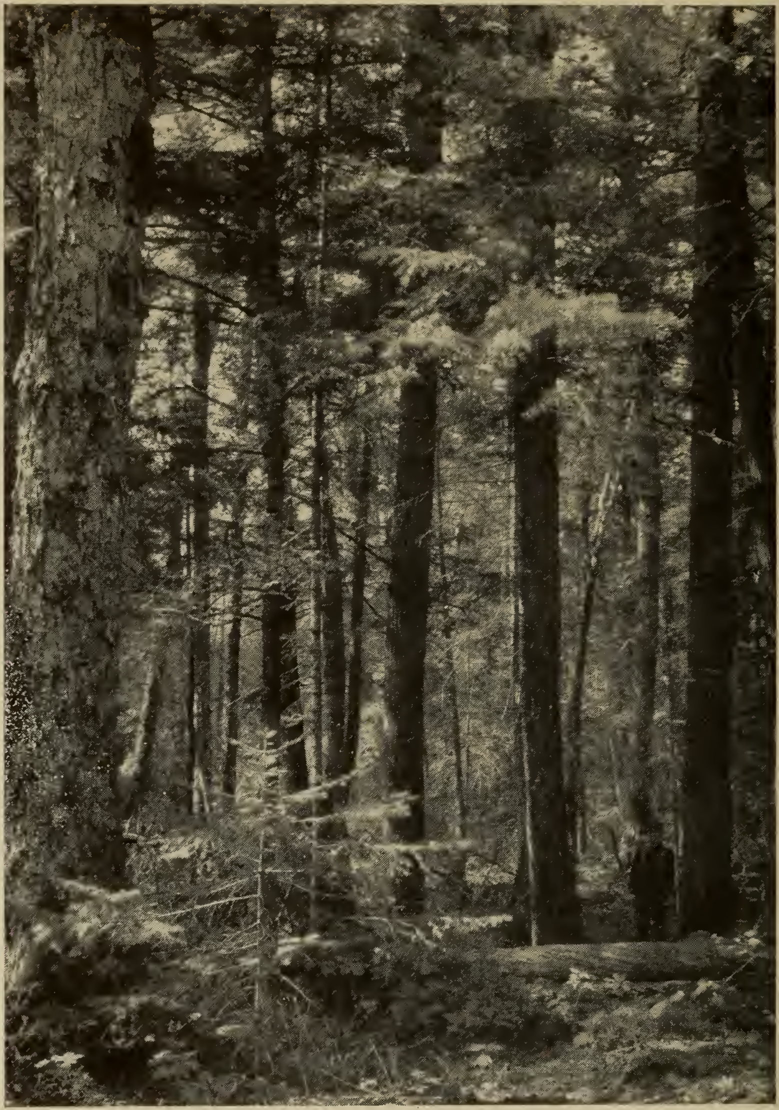


FIG. 10–18. Virgin stand of hemlock and yellow birch on podzol loam of a terminal moraine, *Clintonia-Lycopodium type*. (U. S. Forest Service.)

on a substratum of a pH 8.1. Occasionally, the matted mor is replaced by a black, pulverized detritus of organic matter produced largely by arthropods and varying in thickness from 2 to 10 inches. This thick, superficial deposit of raw organic remains is known under the questionable term of "fine mull."

Calcareous podzols support predominantly white spruce, black spruce, balsam fir, white pine, hard maple, and other deciduous species. The ground cover includes raw humus plants, common to the fine-textured noncalcareous podzols of strongly acid reaction. The pioneer stands are formed predominantly by trembling aspen and balsam poplar. The yields of virgin stands at times approach 120 Mbf per acre. Second growth stands of aspen are characterized by a very close density, and their yields may be as high as 60 cords per acre at the age of seventy years.

Gley-podzolic soils. Within the boundaries of the northern forests, the proximity of the ground water is usually paralleled by the process of podzolization. The resulting varieties of gley-podzolic soils differ in their floristic cover and productive capacity depending upon the textural composition and the distance of the gley horizon from the surface.

Gley-podzolic soils of sandy texture predominantly support stands of white pine with some red pine, balsam fir, black spruce, aspen, and paper birch. The deep gley soils vary only slightly from sandy podzols, except that they have a somewhat higher productivity, a better developed layer of shrubs, and a ground cover characterized by the presence of *Rubus hispidus,* abundant *Cornus canadensis,* and a nearly continuous carpet of mosses, especially *Polytrichum.* The yield of white pine stands on these soils has been recorded to attain in some instances 40 Mbf per acre at the age slightly exceeding one hundred years. The shallow-gley sandy soils, or swamp-border sands, are occupied largely by white pine with some aspen and paper birch and an understory of balsam fir and black spruce. The ground cover is made up of *Polytrichum, Sphagnum,* other mosses, and a sprinkling of bog plants, such as *Ledum groenlandicum, Eriophorum,* and *Scirpus.* The yields seldom exceed 15 Mbf per acre.

Gley-podzolic loams and clays are not readily distinguishable from their better-drained textural relatives until the mottling of the gley horizon appears at a depth of less than 3 feet. This is commonly reflected in the development of a root mor or saprogenous mor layer. The forest cover of these soils includes a melee of hard maple, red maple, yellow birch, elms, black ash, white pine, hemlock, balsam fir, and spruces. Hard maple often dominates the stand but has poor form and slow growth. The shrub story includes hazelnut, gooseberry, currant, dogwood, meadow-sweet, tag alder, mountain maple, mountain ash, willows, and witch hazel. The ground cover varies considerably but is conspicuously marked by the occurrence of several raw humus and moisture-loving plants—*Galium triflorum, Equisetum sylvaticum, Impatiens biflora, Oxalis montana, Linnaea borealis, Carex* spp., and ferns, particularly species of *Athyrium*. The yields vary between 9 and 20 Mbf per acre at one hundred years rising in direct relation to the percentage of conifers. After logging or severe fire, podzolized gley loams and clays are often invaded by sedges, willows, tag alder, black ash, mountain maple, mountain ash, and struggling aspen or paper birch.

If one should follow the medicine-borrowed nomenclature of European foresters, the fine-textured shallow-gley loam podzols of America present a problem of chronic sickness that can be cured only by a radical operation—the dredging of drainage ditches across the area. However, under present conditions the cure may cost more than the sound body of the soil is worth.

Muck soils; Urtica-Galium type. These soils of stream bottoms exhibit a deep, black, sapropel-like layer formed by a retarded decay of plant remains and a deposition of mineral and organic material during inundation. The forest cover is composed of water-loving hardwoods and conifers with an understory of tag alder, willows, dogwood, and elderberries and a dense cover of *Urtica dioica, Laportea canadensis, Thalictrum dasicarpum, Galium* spp., ferns, grasses, and sedges. The yields of northern bottomland hardwoods seldom exceed 7 Mbf per acre at the age of one hundred years; the yields of conifers may be as high as 15 Mbf per acre.

Woody peat; Oxalis-Coptis type. The partly disintegrated wood of dark-brown color and slightly acid or neutral reaction is slimy to the touch and emanates the disagreeable odor of hydrogen sulfide. The slow-moving ground water moderates to some extent the deoxygenation of the deeper horizons and enriches the deposit in nutrient salts.

The forest cover consists of either white cedar with some balsam fir, spruces, and tamarack, or of black ash, elms, red maple, and tag alder. Sometimes hardwoods and conifers form mixed stands. The ground cover resembles that of hemlock stands but is distinguished by an abundance of *Coptis trifolia, Oxalis montana,* ferns, and mosses of *Polytrichum, Hypnum, Hylocomium, Mnium,* and *Leucobryum* genera. Under favorable conditions stands of white cedar and its associates produce as much as a half cord per acre per year.

Moss peat; Ledum-Chamaedaphne type. The lower strata of the organic deposit are composed by partly decayed aquatic plants which are superseded by sedges and finally a deep layer of dead moss. The reaction of young moss-peat deposits is determined largely by the nature of the substratum and the hardness of the ground water; in some cases it approaches neutrality. The reaction of old deposits is invariably strongly acid because of the irreversible fixation of bases by *Sphagnum*.

Moss peat supports black spruce and tamarack, the only two species of value that can dwell on this organic soil (Fig. 10–19). At times these are accompanied by a dwarfed adventurer from the arctic region, *Betula pumila*. The members of the ground-cover vegetation include *Sphagnum* spp., *Chamaedaphne calyculata, Ledum groenlandicum, Kalmia polifolia, Andromeda glaucophylla, Vaccinium macrocarpon, V. oxycoccus, Cypripedium* spp., *Scirpus cyperinus,* and carnivorous "fly-catchers"—*Drosera rotundifolia* and *Sarracenia purpurea.*

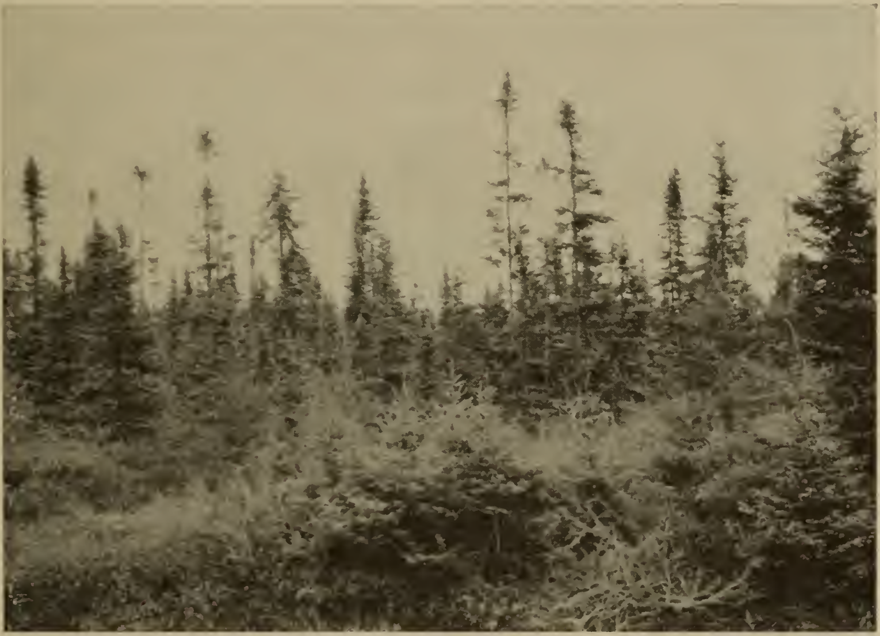
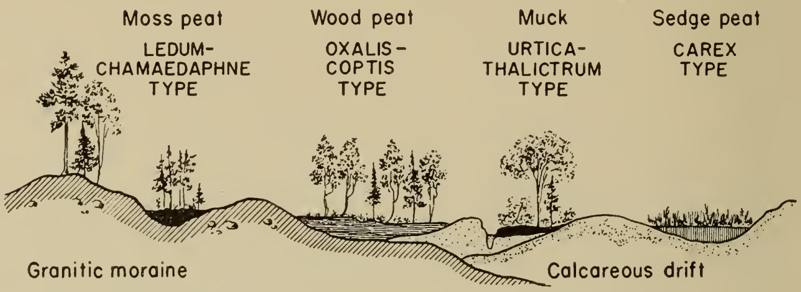


FIG. 10–19. Mixed stand of black spruce and tamarack on moss peat of *Sphagnum-Ledum-Chamaedaphne* type; some trees are over 100 years old. (U. S. Forest Service.)

The growth of trees on moss peat is influenced by the content of electrolytes and the degree of ground water oxygenation. On reasonably well-oxygenated deposits, black spruce attains a yield of about 12 cords per acre at the age of forty years. Tamarack occasionally shows a nearly doubled rate of growth. On stagnant bogs the entire area may be occupied by *Sphagnum* and low shrubs.

Sedge peat; Carex type. Deposits of partly decomposed sedges, reeds, rushes, and cattails occur as infrequent intrusions in the forests of the north, being largely confined to kettle holes of calcareous deposits. These marsh lands provide refuge for wildlife and constitute an important auxiliary item in the household economy of the podzol region.

Figure 10–20 illustrates the predominant chemical composition of ground water observed in different organic soils of northeastern Wisconsin.



Reaction (pH)	4.16±.03	6.10±.12	6.49±.10	7.02±.07
Specific Conductance (mhos.)	7.85±.76	22.11±1.93	37.96±3.07	68.30±3.12
Redox (mv.)	−255±13.5	−49±6.9	+19±6.8	+52±8.0

Fig. 10–20. Chemical characteristics of ground water underlying different types of organic soils in northeastern Wisconsin. (After Wilde, Trach, and Peterson, 1950.)

PRAIRIE FORESTS OF THE DNIEPER WATERSHED, SOUTHERN RUSSIA

> *It was ever the same boundless, waving, beautiful steppe. Only at intervals the summits of distant forests shone blue, stretching along the banks of the Dnieper.*
>
> —Gogol, "Taras Bulba"

The forests of the Dnieper valley for a long time played an important role in the history of the Ukrainian prairie. In the early days they served as a refuge for wandering Mongolian tribes. Later, white outlaws and runaway serfs used these forests as their headquarters and spied from here upon their prey in the surrounding prairies. Ukrainian cossacks camped here during their many marches to and from battle. In the middle of the nineteenth century, forest tracts of this region were placed under planned management based on the principles of imported German silviculture. After many years of experimentation with the shelterwood system and clear cuts followed by artificial reforestation, foresters had to admit that their efforts brought more disastrous than beneficial results (Khitrovo, 1911). Only after the differences in soils and other growth factors were explained was the management placed on a sound basis of careful selection cuttings that prevented replacement of valuable oak and ash stands by hornbeam (Morozov, 1930).

A section of the Russian prairie forest, the "Cherny Les," is selected for a detailed description because of its dissected topography and sharply expressed influence of soils on the composition and the rate of growth of forest stands.

The temperature of this forest tract averages 70° F. for July and 18° F. for January, the coldest month. Average annual precipitation is 20 inches, but the rainfall is very irregular. Average humidity approaches 75 per cent. The geologic substratum of granites and gneisses of pre-Cambrian age is capped by tertiary and post-tertiary deposits, and in turn covered with a deep blanket of loess. Because of intensive erosion, the surface geology presents a mottled appearance. On uplands, the depth to the ground water is about 50 feet; in the eroded valleys it is accessible to deep-rooted trees.

The genetic nature of soils and the distribution of forest types are closely related to the topographic features of the land and permit the recognition of the four ecological units: plateau oak forests on degraded chernozem; upper slope oak-ash forests on dark grood loams; lower slope oak-ash forests on leached grood loams, and cove oak forests on podzolic loams (Fig. 10–21).

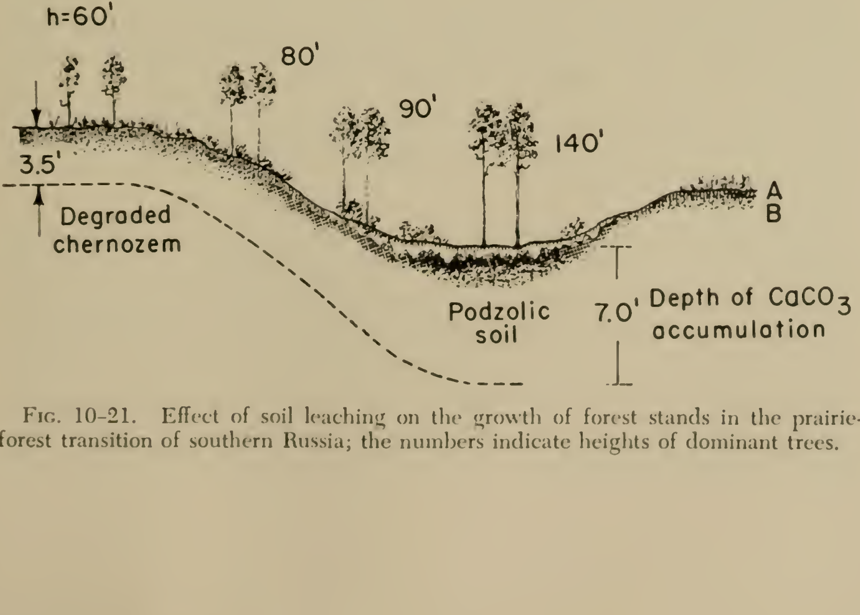


FIG. 10–21. Effect of soil leaching on the growth of forest stands in the prairie-forest transition of southern Russia; the numbers indicate heights of dominant trees.

Oak type of plateaus. The soil is slightly degraded chernozem derived from loess and underlain at a depth of about 3 feet by a zone of lime accumulation. The forest cover of summer oak, *Quercus pedunculata,* with an understory of maple and basswood has a low site index and yields only a dozen cords at maturity. Ground-cover vegetation is characterized by abundant *Sisymbrium alliaria,* and the type is referred to as *Quercetum sisymbrianum.* Its prairie border is fringed by sporadic clumps of trees. At a distance from the prairie, degradation of the soil becomes more pronounced, and the dominant trees reach a height of 80 feet.

Oak-ash type of the upper slopes. The soil is a degraded chernozem or an embryonic grood silt loam exhibiting a deep, dark horizon with incorporated humus and a brownish-gray nut-structured *B* horizon. The parent material of loess is impoverished in carbonates to a depth of 4 or 4½ feet. The forest cover is made up of oak and ash, the latter species contributing from 30 to 50 per cent of the stand's volume. The understory includes basswood, hornbeam, elm, and dwarf maple, *Acer campestris.* The ground cover of *Quercetum stellarianum* type is dominated by *Stellaria holostea, Sisymbrium alliaria,* and *Carex* spp.

Oak-ash type of the lower slopes. Areas of this topography receive an increased supply of water and develop leached grood soils exhibiting a light-gray eluvial horizon and a nut-structured accumulative layer; the zone of effervescence in some profiles is as deep as 5½ feet. The light-gray veins of bleached soil extend to a considerable depth, lining the root channels and structural crevices.

Forest cover is formed largely by oak, with 10 to 20 per cent of ash and an understory of hornbeam, maple, basswood, and hazelnut. The ground cover consists predominantly of *Carex pilosa* and *C. digitata* with some *Stellaria holostea, Asarum europeum, Viola* spp., and *Geum urbanum.* This type is designated as *Quercetum caricetum.* Individual oak trees attain a height of 93 feet, and the yields approach 12 Mbf per acre.

Oak type of coves. Soils of this type are confined to nearly flat bottoms of the valleys which receive a considerable share of runoff. Some water from melting snow accumulates in the depressions of microrelief and saturates the soil through a greater part of the growing season. The strong leaching imparts an acid reaction to the solum, obliterates structural features of the *B* layer, and lowers the zone of carbonates to a depth as great as 7 feet. Consequently, the soils are classed as podzolic.

Forest stands are composed entirely of oaks, largely *Quercus pedunculata*, var. *tardiflora*, a variety characterized by a delayed flowering. The understory is made up of maple, basswood, and hornbeam. The ground cover consists chiefly of *Aegopodium podagraria* with some *Mercurialis perennis, Stellaria holostea, Asperula odorata, Polygonatum officinale, Cardamine impatiens,* and *Gypsophyla paniculata.* Some of the dominant oak trees reach the great height of 140 feet, and the yields may exceed 20 Mbf per acre. The cove soils of loessial deposits provide site conditions responsible for the respect paid to the oak by people of Europe, a respect which inspired Mickiewicz to write: "The tales of wonders and the legends of centuries old told to me by the cloud-splitting oak . . ."

PRAIRIE FORESTS OF THE DRIFTLESS AREA OF WISCONSIN, U. S. A.

> *First of all, the earth girdled its hills with a green glow of herbage. Then trees were given free rein to join in an eager race for growth into the gusty air.* —Lucretius, 70 B.C.

At the northern boundary of this region, preglacial topography arrested the movement of ice, and a large area of sandstone and limestone hills escaped the rejuvenating effect of the glacier. The scars and wrinkles caused by denudation which proceeded for millions of years restricted the possibilities of agricultural land utilization. In return the dissected topography of the driftless area with its numerous crags, pinnacles, natural bridges, sink holes, and caves, presented inhabitants with a picturesque miniature of the Lower Alps or Small Carpathians. The contact of the recent and ancient geologic formations permitted an insight into the dynamics of the earth and its vegetative cover.

The alternation of erosion-exposed siliceous and calcareous substrata, occurrence of loess blankets and deposits of overwash, variation in microclimatic conditions on different slopes, and participation of prairie and forest vegetation have produced here a highly diversified mosaic of soil-forest units (Fig. 10–22). The most important types are briefly described following reports of Whitson (1927), Wilde, Whitford, and Youngberg (1948), and Youngberg and Scholz (1950).

Forested blackearths or embryonic grood loams; Andropogon-Sorgastrum type. Morphologically, and to a great degree ecologically, these dark soils are similar to prairie soils of the Tama series.

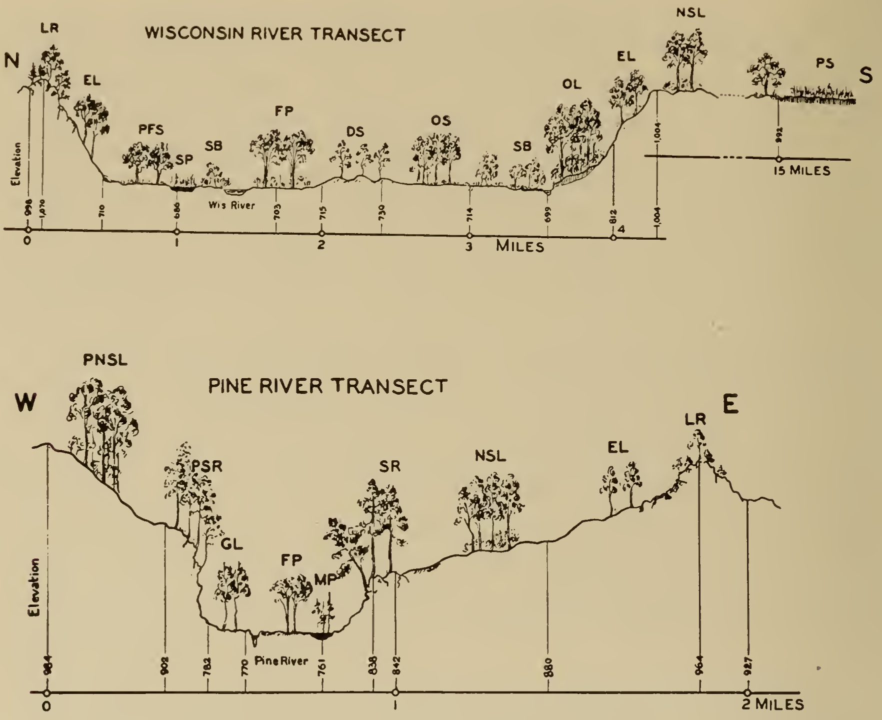


Fig. 10–22. A schematic outline of the soil-vegetation units encountered on north-south and east-west transects in the prairie-forest transition of Wisconsin. *LR*: Limestone rockland—bur oak, red cedar; *EL*: Eroded loam—oaks; *PFS*: Embryonic grood loam—savannah-like stands of bur oak; *SP*: Sedge peat; *SB*: Stream bottom—willows; *FP*: Flood-plain soils—elm, swamp white oak, river birch, soft maple; *DS*: Dune sand—jack pine; *OS*: Outwash sand—jack pine, scrub oaks; *OL*: Overwash grood loam—white oak, red oak, white ash, hickory, black walnut, hard maple, basswood; *NSL*: Leached grood loam—oaks and hickory; *PS*: Prairie soil—blue stem, Indian grass; *PNSL*: Podzolized grood loam—hard maple, basswood, red oak; *PSR*: Podzolized sandstone rockland—hemlock, yellow birch; *SR*: Sandstone rockland—white pine, red pine. (After Wilde, Whitford, and Youngberg, 1948.)

Their cover consists of scattered bur oak and prairie plants, particularly *Andropagon* spp., *Bouteloua curtipendula*, *Stipa spartea*, and *Sorgastrum nutans*. The original prairie vegetation, however, at present is largely replaced by orchard grass and other invaders (Fig. 10–23). The distribution and growth of trees on these soils is hindered by the absence of mycorrhizal fungi, virulence of damping-off disease, dense population of rodents, competition of grasses, and lethal transpiration during cold snowless periods (White, 1941).

Leached grood loams; Parthenocissus-Circaea type. The leached, nut-structured soils support the largest share of forest stands of the region. They are formed either on residual limestone (Fayette

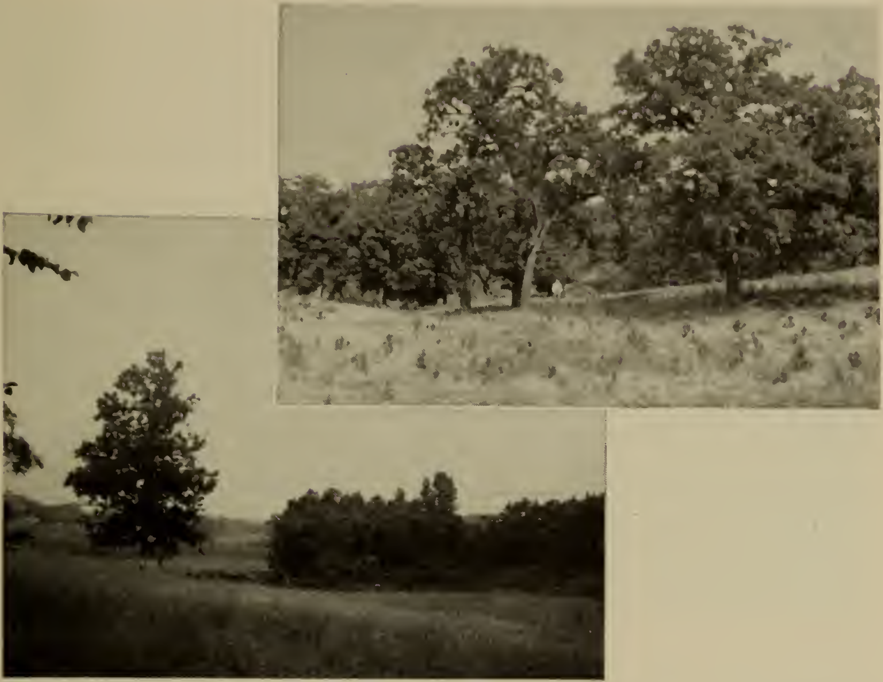


Fig. 10–23. Prairie forest landscape. The open-grown trees are characteristic of dark or embryonic grood soils.

series) or on loess (Dubuque series). The forest cover includes white, red, and black oaks, hickories, black walnut, elm, and box elder. In advanced stages of succession, these species are accompanied or replaced by hard maple and basswood. The ground vegetation is characterized by the presence of *Parthenocissus vitacea, Circaea latifolia, Geranium maculatum, Phryma leptostachys,* and *Desmodium acuminatum.*

In spite of their excellent structure and abundant supply of nutrients, these soils produce only modest yields of timber, seldom exceeding 10 Mbf per acre (Fig. 10–24).

Podzolized loams; Mitchella-Polygonatum type. The two prominent features revealing podzolization of the nut-structured prairie-forest loams are a layer of matted organic remains and the occurrence of herbaceous plants common to raw humus soils. The forest stands consist of hard maple, basswood, and red oak with ground cover of *Mitchella repens, Hepatica* spp., *Polygonatum pubescens, Uvularia grandiflora,* and *Mitella diphylla.* Hard maple on these soils possesses a high capacity for natural regeneration. The yields average 12 Mbf per acre.

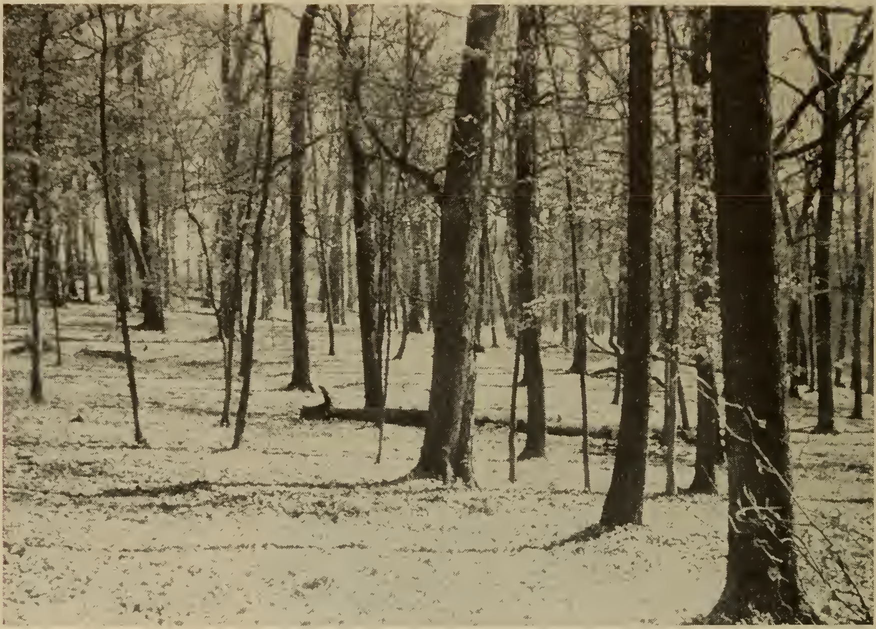


Fig. 10–24. Stand of black and red oaks on a leached grood silt loam. This mediocre quality timber is supported by one of the world's most productive agricultural soils.

Overwash grood loams; Dicentra-Impatiens type. The genetically mature soils of the lower slopes are distinguished by a pronounced nut-structure of the *B* horizon and a deep, dark surface layer, which impart to the soil profile an appearance of a blackearth. In fact, these most productive forest soils of the region have been often mapped as "prairie soils" (valley phase of the Tama series).

Forest cover is made up of white oak, red oak, hard maple, basswood, white ash, and black walnut, accompanied by a dense understory of shrubs (Fig. 10–25). The rich ground association includes *Dicentra cucullaria, Impatiens* spp., *Asarum canadense,* and *Sanguinaria canadensis.* Fully stocked stands produce nearly 15 Mbf per acre. In many instances, the growth of trees is stimulated by seepage. The high productive capacity of these soils requires extremely conservative regeneration cuttings protecting valuable species against undesirable invaders: elm, ironwood, and gray dogwood.

Limestone rockland; Buteloua type. The youthful rendzinas of limestone outcrops exhibit a shallow, dark surface layer which grades into a partly weathered regolith. The vegetative cover is composed of prairie plants, *Buteloua hirsuta, Asclepias verticillata, Anemone*

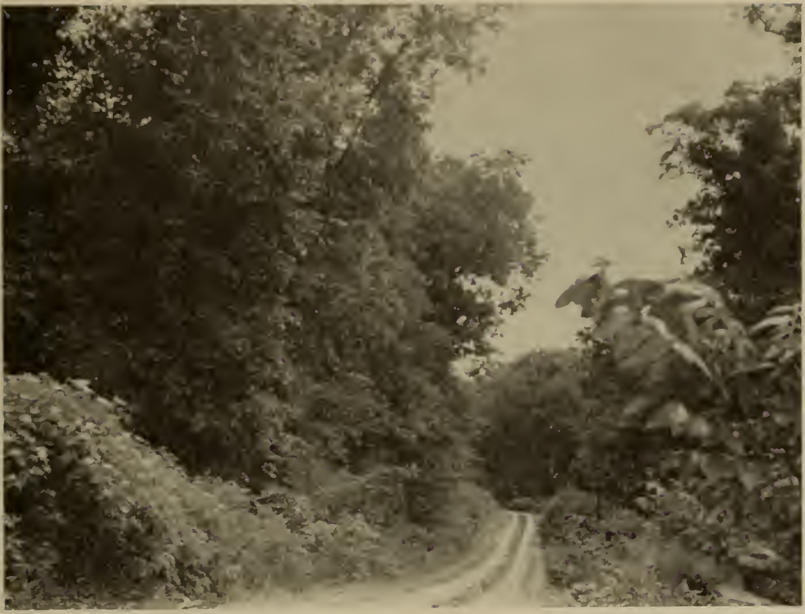


FIG. 10–25. Forest cover of oaks, hard maple, basswood, and other hardwoods on overwash silt loam. This is the most productive type of the prairie-forest transition of the American Midwest.

patens, and *Euphorbia corollata.* Scattered bur oak, red cedar, and juniper serve to ornament these picturesque but unproductive "goat prairies" (Fig. 10–26). The height of bur oak is often only 25 feet at the age of 150 years.

Dune sands; Cladonia-Hudsonia type. The wind-reworked hills of sandy terraces support stands of jack pine struggling on these dry and infertile deposits and yielding only a half dozen cords per acre. The sporadic ground cover is made up of *Cladonia* spp., *Hudsonia tomentosa,* and xerophytic grasses. The unusual feature of these sands is the occurrence of a cactus, *Opuntia rafinesquii,* a witness of a desert-like shortage of moisture.

Outwash sands; Baptisia-Tephrosia type. The purely siliceous sand of river terraces is another soil with a critically low supply of nutrients. The dark, humus-enriched layer of these soils, attaining at times a depth of 1 foot, completely misrepresents the state of soil fertility. The invasion of jack pine and "scrub" oaks imparts to these prairie sands a thin layer of litter but otherwise does not change their morphology. It seems that the poverty of these soils renders impotent the forces of both prairie and forest and thus condemns the two antagonists to eternal struggle with no hope for a victory.

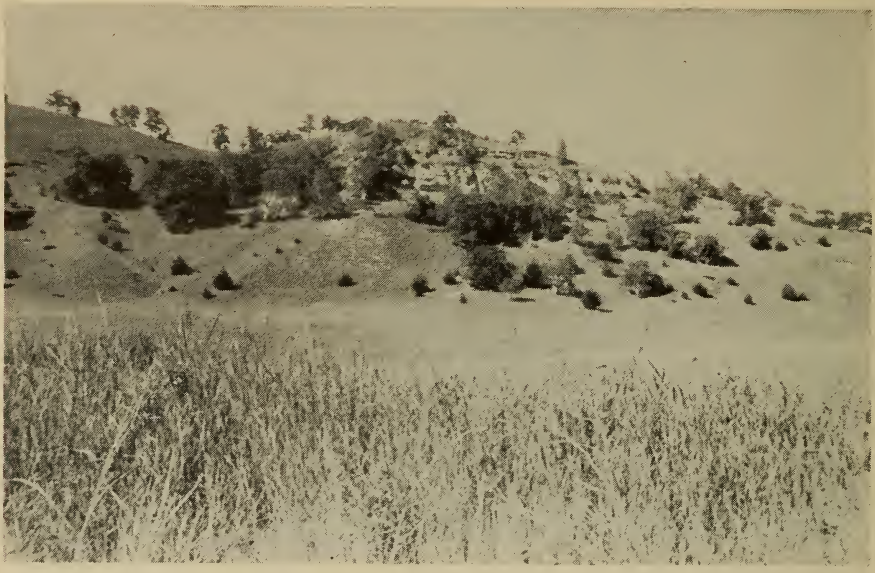


Fig. 10–26. "Goat prairie" of southwestern Wisconsin, shallow rendzina or limestone rockland supporting open stands of bur oak, red cedar, and juniper.

The ground-cover vegetation consists largely of prairie plants common to sandy soils, such as *Baptisia leucantha, B. leucophea, Tephrosia virginiana, Helianthemum* spp., and *Rumex acetosella.* The abundance of legumes indicates a critical deficiency, not a high content of nitrogen.

Jack pine occasionally yields as many as 10 cords per acre at the age of forty years. The better rate of forest growth coincides with the advent of podzolization, manifested in the "salt and pepper" appearance of the melanized horizon.

Sandstone rockland; Gaylussacia-Vaccinium type. Sandstone outcrops are capped with a mantle of weathered material, a few inches thick and somewhat enriched in humus. They support white and red pine with a ground cover of *Gaylussacia baccata, Vaccinium angustifolium, V. myrtilloides, Pteridium latiusculum, Campanula rotundifolia,* and *Aquilegia canadensis.*

In spite of their shallow depth the surface layer of these immature soils has a higher content of colloids, organic matter, and available nutrients, especially exchangeable calcium, than do outwash and wind-blown sands. The pine stands attain on these adverse sites rather high yields of 7 Mbf per acre at the age of about 80 years.

Podzolized sandstones; Epigaea-Polypodium type. This is one of the paradoxical soil-forest units of the region. It is confined to outcrops of sandstone bordering protected river coves or located on cool northern and eastern exposures. In spite of a very shallow mantle of weathered material, the profile is of a distinct podzol morphology with strongly acid, matted raw humus, a 1- or 2-inch-thick bleached layer, and a reddish-brown accumulative horizon merging with unweathered sandstone.

The forest cover consists of the two erratic members of the northern forests—hemlock and yellow birch. Occasionally, stands include white pine. The ground vegetation is characterized by the presence of *Epigaea repens*, *Polypodium virginianum*, and *Gaultheria procumbens*—the faithful associates of hemlock and white pine forests of the north. These patches of forest cover on podzols, totally uncommon on other soils of the prairie-forest region, are museum pieces illustrating that the ecological effect of substratum sometimes cannot be overruled by the pressure of predominant local vegetation.

Gley grood loams; Galium-Ranunculus type. The soils of the marsh borders are characterized by a deep layer with infiltrated humus and a bluish-green, mottled-gley horizon of prismatic structure. Forest stands consist of white and slippery elm, black oak, some red oak, aspen, paper birch, and alder. On soils with a gley horizon near the surface, cottonwood and willows replace most of the other trees. The ground cover is greatly diversified but is marked by the presence of *Ranunculus septentrionalis*, *Galium* spp., *Hydrophyllum virginianum*, and *Laportea canadensis*. The yields vary between 4 and 7 Mbf per acre; the wood is of very poor quality, and a greater part of the stand is often infected with fungi (Fig. 10–27).

Flood plain soils; Urtica-Cephalanthus type. Periodic inundations and the proximity of the water table restrict the composition of forest cover of these soils to phreatophilic species, such as white and slippery elms, black ash, white swamp oak, river birch, silver maple, cottonwood, and willows. The ground vegetation is characterized by the presence of *Urtica procera*, *Cephalanthus occidentalis*, *Mentha* spp., *Onoclea sensibilis*, and *Lysimachia ciliata*. The rate of growth is subject to wide variations, but the volume of merchantable timber is often very low because of poor quality of wood and high percentage of cull.

Moss peat; Sphagnum-Chamaedaphne type. In all probability the islands of the extremely acid peat bogs, interspersed among calcareous hills, present relics; but their exact origin and history is wrapped in mystery. The only tree inhabiting these organic soils is tamarack, which shows a comparatively rapid annual growth of about 0.3 cords per acre. The erosion, accelerated during the last century by cultivation and grazing, often covered the moss peat with a blanket of over-

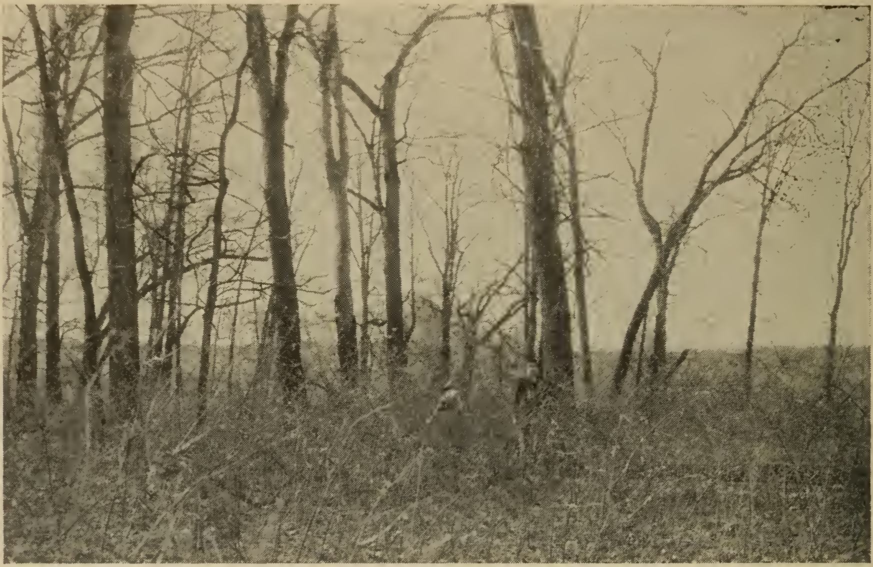


Fig. 10–27. Deteriorating stand of black oak, slippery elm, and boxelder on a gley-grood loam bordering sedge marsh.

washed silt. This, in turn, greatly modified the original *Sphagnum-Chamaedaphne* association by invasion of foreign species.

Sedge peat; Carex-Scirpus type. The alkaline layer of nearly black, macerated organic matter is underlain by a mottled, structured marl or "blue clay." The cover of *Carex* and *Scirpus* spp., *Typha latifolia, Iris virginica, Spartina pectinata,* and other marsh plants is one community of the prairie-forest transition that never succumbs to the assault of forest vegetation.

SOIL-FOREST TYPES OF LES LANDES IN THE GASCOGNE PROVINCE, SOUTHWESTERN FRANCE

> *Our itinerary led us to traverse the extensive barrens, called "Les Landes" . . . Only at long intervals we passed small woodlots which, however, did not enliven the countryside. These were plantations of pine, pruned to the tops; their trunks bore deep scars which shed resin as white, crystal-like tears.*—Hector Malot, "*Sans famille.*"

There are but a few areas in the world which can compare in ecological simplicity with certain sections of the sandy plains of the Gascogne Province, described by Duchaufour (1948).

The warm and humid oceanic climate of this region is not too different from that of its Trans-Atlantic counterpart, the Coastal Plain of the southern United States. Upon superficial observation the stands of maritime pine and various species of oak, comprising forest cover of Les Landes, resemble the pine-oak types of America. The similarity of these two regions, however, ends right there. The uniform parent soil material of the French coastal plains is formed by deposits of pure silica, by and large reworked by wind. The outline of the most outstanding soil-forest types follows (Fig. 10–28).

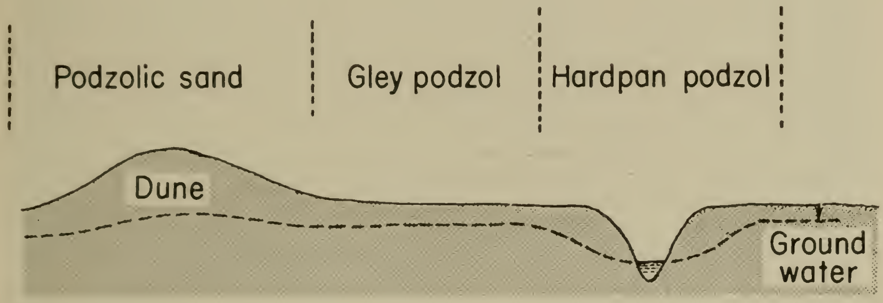


FIG. 10–28. Distribution of soils in relation to topography and ground water table in Les Landes of the Gascogne province of France. (After Ph. Duchaufour, 1948.)

Recent aeolian deposits. The profile of "young" dunes is formed by pure, nearly white quartz sand covered with a thin layer of litter and exhibiting a more or less pronounced A_1 horizon. In advanced stages of development, however, dune sands are infiltrated with humate suspensions to a depth as great as 20 inches and attain a strongly acid reaction.

Because of man's influence, the forest cover is made up largely of *Pinus pinaster*; the autochthonous oaks, *Quercus pedunculata*, *Q. suber*, *Q. ilex*, and *Q. toza*, largely form either a codominant or suppressed fraction of pine stands. The shrub layer and ground-cover vegetation include many species common to Mediterranean flora. The most prominent members of the association are: *Ilex aquifolium*, *Ruscus aculeatus*, *Ulex galii*, *Arbutus unedo*, *Erica scoparia*, *Cistus salviaefolius*, and *Teucrium scorodonia*.

The inadequate supply of nutrients and buffering colloids are reflected in a low site quality of stands producing but a few cords per acre (Fig. 10–29).

Podzolized sands. In spite of the constant rejuvenating effect of wind erosion, sandy soils of uplands have a tendency to undergo podzolization. The initial stages of this process are manifested by an

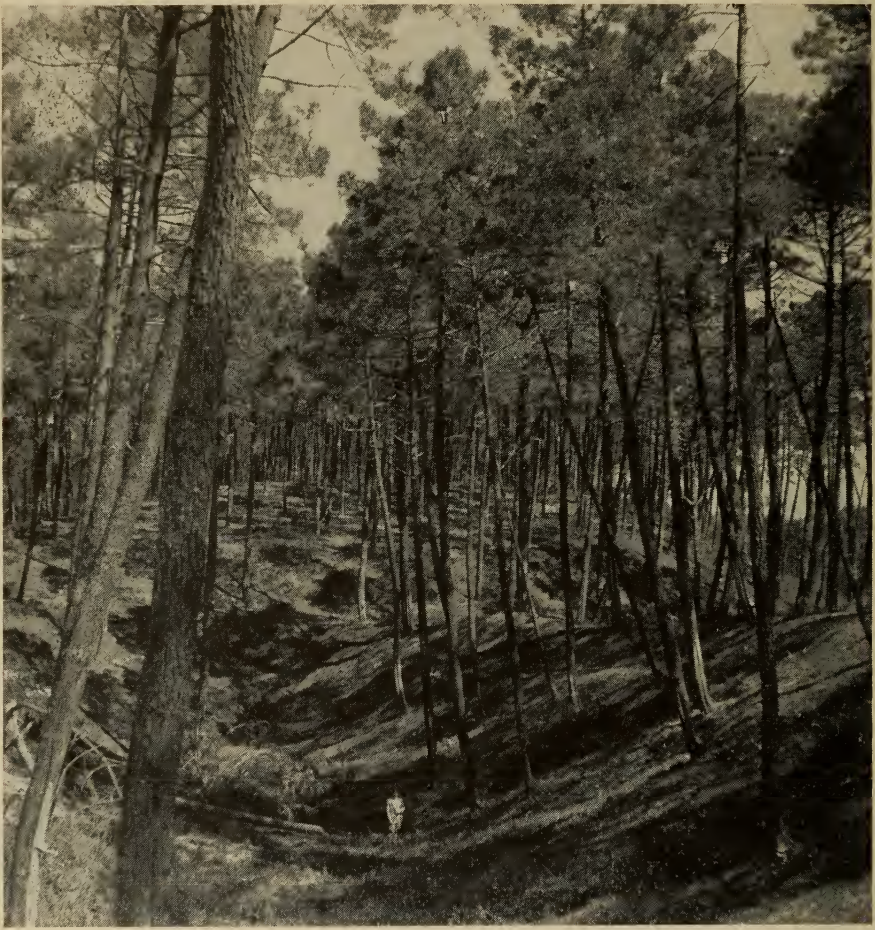


Fig. 10–29. Stand of maritime pine on a sand dune in the district Jous (Landes). The absence of ground cover vegetation reflects the immaturity and the low productive capacity of the soil. (École National des Eaux et Forêts.)

enrichment of the lower soil stratum in iron oxides. Yet, the surface soil usually retains its organic matter and dark color in spite of eluviation. In part the process of podzolization is retarded by the removal of litter by farmers—an act precluding the invasion of podzol-forming heather plants, particularly *Erica cinerea, E. scoparia,* and *Calluna vulgaris.* Under such circumstances the ground-cover vegetation is dominated by *Pteris aquilina* and *Ulex europea.*

The moderately podzolized soils are the most productive sites of the region (Fig. 10–30). Unfortunately, their productive capacity is usually decreased by perpetuation of pure stands of maritime pine and subsequent elimination of soil-conserving oaks.

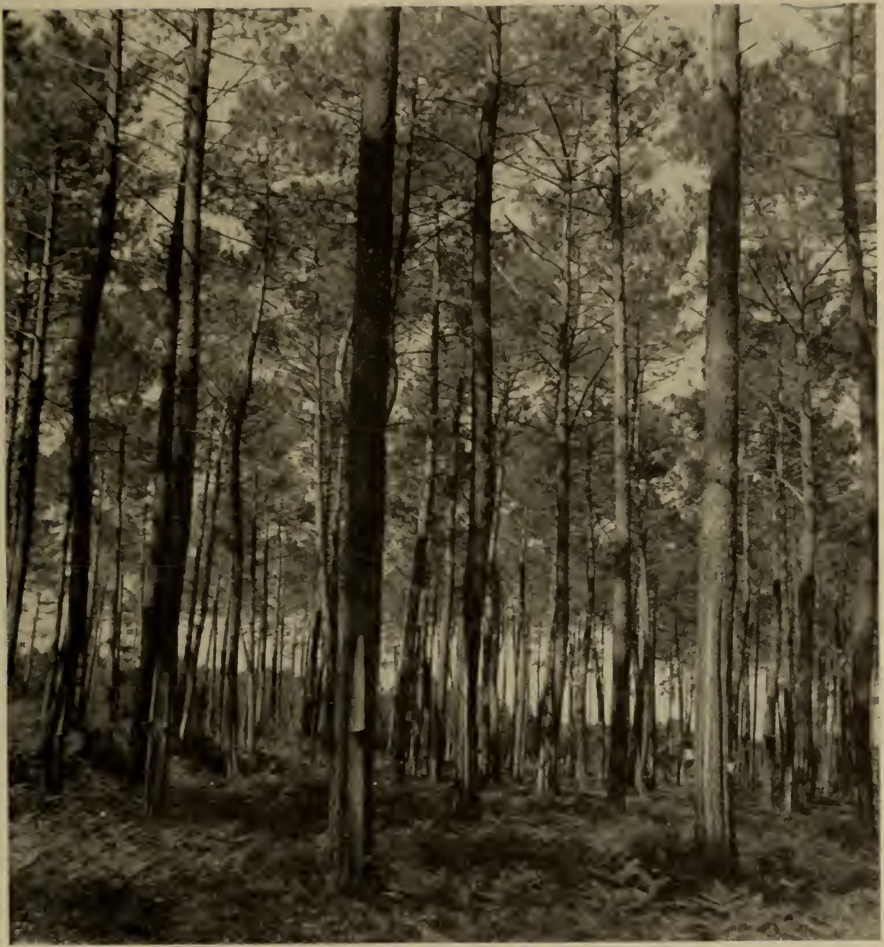


Fig. 10–30. Stand of maritime pine with ground cover of bracken fern, *Pteridium aquilinum*, on a strongly acid podzolized sand in the district Lugacon (Landes). This is an example of the most productive forest cover of the region. (École National des Eaux et Forêts.)

Sandy podzols. On better-drained lowlands, the podzolization process climaxes in the development of a pronounced leached horizon of ashy gray color and a firmly cemented hardpan. The latter often is underlain by a zone periodically saturated with free water. The accumulative layer attains a thickness of 2 feet; its upper portion is enriched in organic matter whose content approaches 4 per cent. The reaction of the soil profile varies from pH 4.5 to pH 5.7.

The forest cover of maritime pine is accompanied by *Erica cinerea* and *Calluna vulgaris*, the members of ground-cover vegetation that promote podzolization.

Sandy gley podzols. The morphology of the gley-podzolic sandy soils of this region is strongly influenced by the seasonal fluctuations of the ground water table. On some sites free water stays only 1 foot from the surface during the winter months but descends in the summer to a depth of about 7 feet. Under such conditions there is an impoverishment of the surface soil in iron, which is reduced to the ferrous state and gradually removed by the ground water. Simultaneously, there is an enrichment of the lower zone in organic matter which imparts a dark color to the transitional *BG* layer. With a reduced amplitude of the ground water fluctuation, however, soils attain the morphology of gley-humus podzols with a dark *B* horizon carrying as much as 7 per cent of organic matter—a content exceeding that of the surface soil.

These hydromorphic soils support stands of pine almost exclusively. The presence of the water table is often revealed by the occurrence of *Molinia coerulea, Erica tetralix,* and *Anthericum planifolium.* These are accompanied by *Erica scoparia, E. ciliaris,* and *Ulex nanus.*

Peat soils. The depressions are filled by deposits of lowmoor peat derived from reeds, bog moss, and heather plants. These organic soils attain a considerable depth and support the typical association of *Sphagnum* species and *Erica tetralix* with sporadic occurrence of *Myrica gale, Drosera anglica, Calluna vulgaris,* and *Molinia coerulea.* Occasionally, the dominance of the bog vegetation is challenged by oak species, *Quercus toza* and *Q. pedunculata*—picturesque ornaments of little silvicultural value on these sites.

SOIL FOREST TYPES OF THE ATLANTIC COASTAL PLAIN, U. S. A.

> *It was a savagely red land, blood-colored after rains, brick dust in droughts . . .*
> —M. Mitchell, *Gone With the Wind*

This great area of marine deposits slopes gently oceanward, and near the coast it is broken by long tidal marshes and inlets reaching far up the shallow estuaries. The climate is warm and humid, with a growing season varying from seven to nearly twelve months. The annual rainfall of 40 or more inches is rather evenly distributed, although drought sometimes occurs in winter. The parent material of clay, sand, and gravel was eroded from the older Appalachians and laid down during the Cretaceous and Tertiary periods. The sea has covered this region and receded several times during the formation of sediments. Upon the last retreat of the ocean the deposits have undergone severe laterization, a process that is still reflected in the low SiO_2/R_2O_3 ratio and red or yellow color of substrata.

In the course of recent centuries, either percolating or vadose water removed some iron and imparted light shades to the surface layers of many soils, a feature which brought into existence the terms "red podzolic" and "yellow podzolic" soils. As often as not, therefore, the "savagely red lands" are eroded substrata whose topsoil is gone with the wind or water. In places the action of wind proved to be a blessing, for it covered the land with a deep blanket of fertile loess. Because of the low elevation and frequent presence of impervious clay sediments, many soils have an impeded drainage.

The forest cover of less fertile lands is made up of longleaf pine, shortleaf pine, loblolly pine, slash pine, and struggling oaks. Productive soils support rapidly growing oaks, butternut, hickories, tulip poplar, ash, beech, sycamore, sweet gum, and magnolia. Alluvial bottoms and bayous, with their picturesque stands of bald cypress, tupelo gum, and red gum, resemble landscapes of the tropics. In the following descriptions the soil-forest types are designated according to the expressive folk terminology of the "Deep South," as quoted by Hilgard (1906).

Pine lands or pine hills. This type occupies extensive areas of rolling or undulating plains with podzolized or vadose soils of feralitic substrata. The soil profile is usually composed of a sporadic cover of litter, a gray-to-light-brown quartzose layer, and a red or yellow substratum of porous clay. These soils are acid, depleted in organic matter and nutrients, and are subject to periodic droughts. The deficiency of humus is partly due to repeated burning, a generally accepted practice in management of southern lands. These unfavorable soil conditions, however, are balanced by the long growing season and abundant total rainfall permitting a rapid growth of less exacting forest trees, particularly pines.

The forest cover consists of longleaf, loblolly, and slash pines with an incidental admixture of oaks. The ground-cover vegetation includes *Cassia nictitans, Tephrosia virginiana, Phaseolus* spp., *Kuhnistera pinnata, Pteris aquilina, Clitoria mariana, Centrosema virginiana, Liatris spicata,* and *Silphium* sp. The yields of loblolly pines at times attain 25 Mbf per acre at the youthful age of 60 years (Fig. 10–31).

On soils severely depleted by fires and previous cultivation the forest cover is formed by shortleaf pine and slowly growing oaks or longleaf pine with understory of palmetto (Fig. 10–32). The ground-cover vegetation of these poor sites is characterized by the occur-

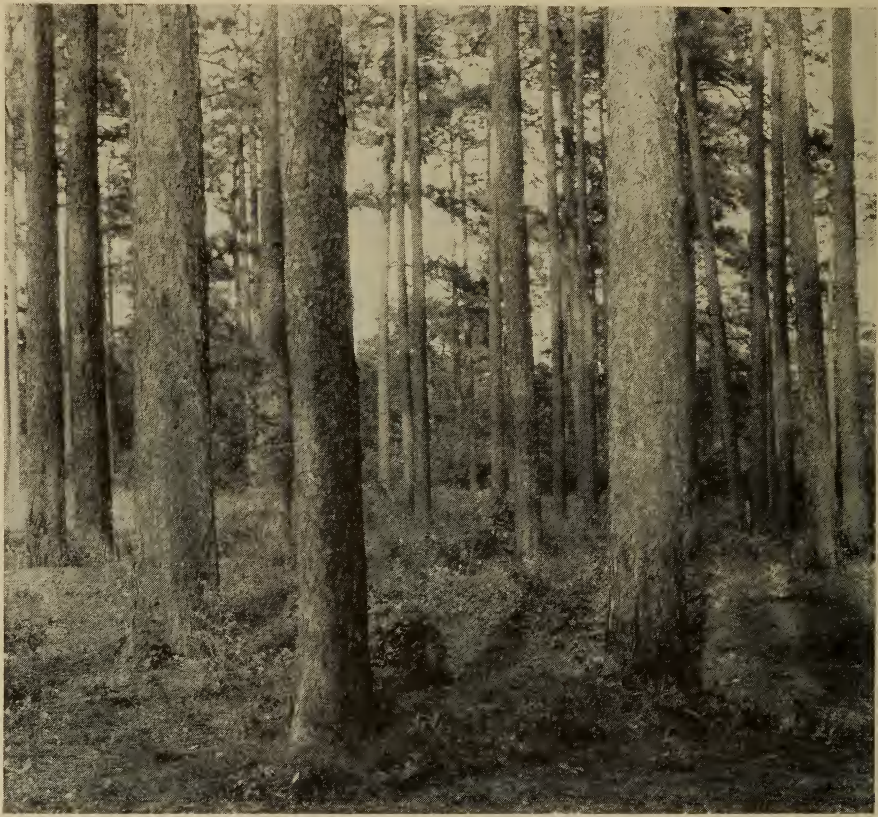


Fig. 10–31. Second-growth stand of loblolly or "old field" pine approximately 60 years old, a common pioneer forest cover on podzolized lateritic soils. (U. S. Forest Service.)

rence of *Aristida stricta, Stipulicida sitacea, Lupinus perennis,* and *Cladonia silvatica.*

The "pine lands" are a widely distributed type which provides a large share of lumber and pulpwood produced south of the Mason-Dixon line.

Flatwoods. Poorly drained acid soils of extensive level areas of the coastal plain proper are the least fertile of the region. They compare in their productive capacity to the soils of northern Russia that bear a similar designation (Rovniad). The strongly leached, light-gray surface layer grades into a water-logged, mottled gley horizon. At times soils are underlain by a hardpan layer characteristic of true podzol soils and are classified as "ground water podzols." The flatwood soils, however, remain covered with a sheet of

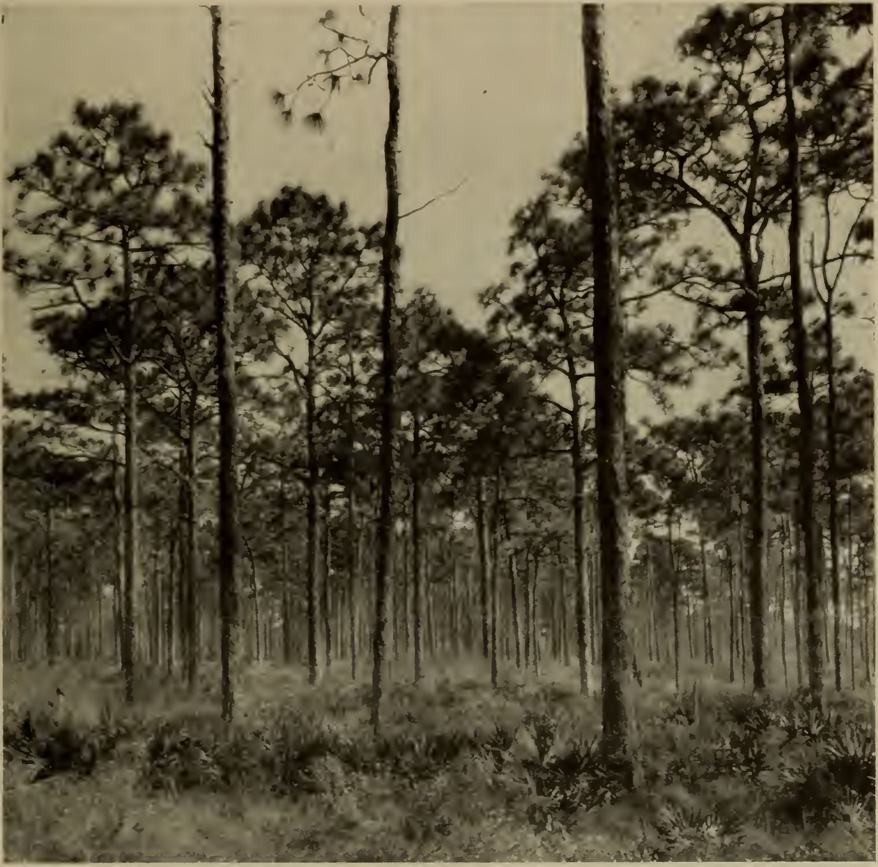


FIG. 10–32. Stand of longleaf pine with understory of cabbage palmetto. (U. S. Forest Service.)

water for a considerable period after heavy rains and in part owe their morphology to surface gleization.

Forest cover is composed predominantly by longleaf pine and dwarfed oaks with ground cover of sedges, rushes, orchids, *Ctenium aromaticum, Dichromena latifolia, Sarracenia flava, Polygala lutea, Colopogon pulchellus,* and *Aletris lutea.*

Near the seashore, flatwoods fade into "pine meadows," a related forest-marsh type.

Sandy hammocks. In the proximity of the ocean the impervious clay substratum occurs at a considerable depth, and the surface deposit of sand is well aerated. As the result, the stands of longleaf pine show a better growth and are enriched in slash pine, loblolly pine, pond pine, and red gum. The low density of stands and the understory of holly, persea, and palmetto impart to this type a tropical appearance (Fig. 10–33). The ground cover is practically free of swamp vegetation.

Shell mounds. The narrow strip along the seashore at times consists of calcareous residue of shells covered by black or dark-gray

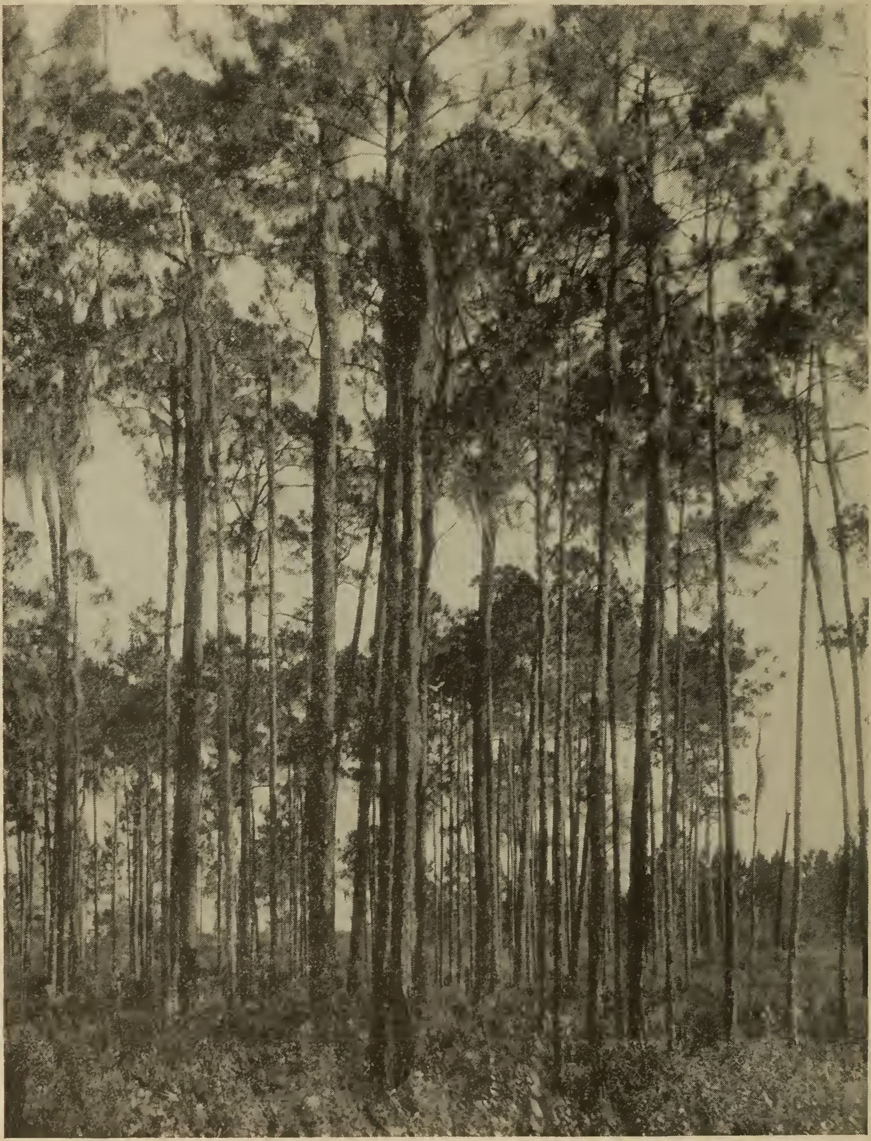


Fig. 10–33. Stand of slash pine robed in a veil of Spanish moss, a forest cover predominant on lateritic soils influenced by ground water. (U. S. Forest Service.)

sand enriched in humus. These deposits support the most picturesque member of the oak family—live oak. *Aralia spinosa, Verbesina,* grape vines, and many legumes are among the common associates.

Table lands. This term implies moderately melanized yellowish-brown or brown loams occupying wide plateaus. These are among the most productive lands of the region considering either agricultural or silvicultural crops. The areas not taken by farming support white oak, red oak, black oak, and Spanish oak, beech, and some walnut. The ground cover is characterized by the presence of *Circaea latifolia, Podophyllum peltatum, Geranium, Vitis riparia, Sanicula gregarea,* and other mesophytic plants of Carolinian flora. The yields of mature stands vary between 20 and 30 Mbf per acre (Fig. 10–34). Pioneer stands are composed largely of oak species.

Bluff soils. The rolling or hilly deposits of calcareous loess adjacent to the Mississippi valley give rise to slightly melanized or crypt-

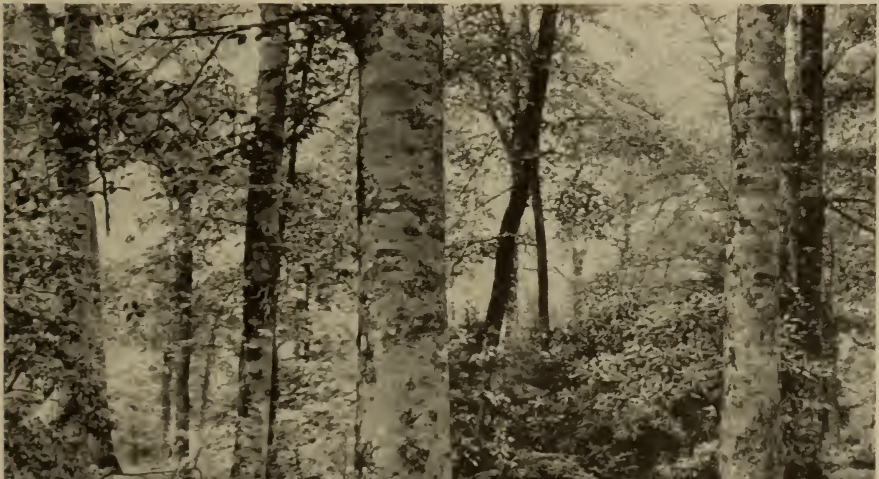


FIG. 10–34. Virgin stand of American beech with understory of rhododendron illustrating the structure of the southern hardwood forest. North Carolina. (U. S. Forest Service.)

organic silt loam soils of a high productive capacity. These soils support rapidly growing and valuable stands of white and red oak, black walnut, ash, and other exacting hardwoods. The stands are accompanied by an understory of shrubs and a rich ground cover of the *Parthenocissus-Circaea* type. The burned-over or logged areas are at times occupied by shortleaf pine and other pines which on these soils attain an exceptionally rapid growth of 1½ cords per acre per year.

Lime prairies. This expression applies to strongly melanized black clays and clay loams formed on weathered, or "rotten," cretaceous limestone. These rendzina-like soils are highly productive under farm crops but support only sparse cover of trees—largely post oak, jack oak, and red cedar. Clumps or thickets of crab apple and Chickasaw plum occur sporadically. In spite of competition of grasses and other herbaceous vegetation, some of the oaks reach large dimensions.

Alluvial soils. Intermittently flooded areas vary greatly in texture, content of nutrients, and degree of ground water oxygenation. These conditions are reflected in forest cover of highly diversified composition and rate of growth.

One of the most distinctive associations, not common to alluvial soils of the temperate region, is formed on inundated soils of flatwoods. It consists of a dense stand of bald cypress with some swamp black gum, slash pine, black willow, and swamp ironwood. The trees are usually dressed in Spanish moss, *Tilandsia usneoides.* The ground cover consists of mosses, ferns, and orchids. In the southern part of the region the association is enriched in members of subtropical flora and may grade into mangrove swamps.

The fine-textured alluvial deposits of the Mississippi River and other streams dissecting the Coastal Plain are occupied by oaks, hickory, bitter pecan, red maple, beech, white ash, elms, sycamore, red gum, tupelo gum, swamp black gum, willows, and bald cypress. The stands have a dense understory of small trees, shrubs, and vines including *Staphylea trifolia, Asimina triloba, Crategus* spp., *Myrica cerifera, Ilex virginica, Tecoma radicans, Cissus arborea, Parthenocissus vitacea,* and *Vitis* spp. The ground-cover vegetation is characterized by the presence of *Phlox divaricata, Arisaema triphyllum,* and *Habenaria ciliaris.* On better-oxygenated portions of stream bottoms, hardwoods produce high yields of valuable timber of a high specific gravity.

Coastal peat. The deposits of peat along the Atlantic shores, called sometimes "pocosins," are formed by dark, partly decomposed remains of wood and herbaceous plants underlain by either sand or clay. Peat on sandy substrata usually supports even-aged stands of southern white cedar which sometimes have a small percentage of pond pine, slash pine, bald cypress, and swamp black gum. On peat underlain by clays hardwoods make the larger part of the stand. The associated vegetation includes *Ilex glabra, Myrica carolinensis, Leucothal acuminata, Lyonia nitida, Baccharis halimifolia, Vaccinium* spp., and the shrubby grass, *Arundinaria tecta.*

Bayous. The areas remaining under water during the greater part of the year are occupied largely by bald cypress. However, near the edges of the bayou this tree is accompanied by tupelo gum, swamp black gum, water oak, and red maple. Palmetto, thorn apple, cane, *Saururus cernuus, Penthorum sedoides, Hypericum* spp., *Lippia lanceolata*, and *Commelina hirtella* are among minor associates. In spite of the isolating sheet of water, stands of bayous produce high yields of timber.

SOILS AND FORESTS OF SWITZERLAND

> *Long would have buried avalanches*
> *The town under the weight of their debris,*
> *Were not it for the bulwark of the forest*
> *That guards against destruction. . .*
> —Schiller, *Wilhelm Tell*

Little can be said in a brief outline about the climate of the land that has a Swiss physiographic diversity. A Russian must travel hundreds of miles from the edge of the spruce forest till he sees a grapevine. A Swiss farmer takes care of his vineyard in the morning and cuts spruce pulpwood in the afternoon; his woodlot may consist of larch on one slope of the valley and chestnut on the other. But lowlands or mountains, gentle breezes from the Mediterranean or frostbiting winds from the Black Forest, the climate of Switzerland on the whole appears to have the same healthy and invigorating effect; its end result is reflected in the past history of the people and their social structure, in the flow of milk, and in the growth of trees which under a planned management provide an annual increment as high as 1 Mbf per acre.

The two major geologic ranges—the old crystalline rocks of the Alps and the calcareous formation of the Jura Mountains—are separated by a broad central plateau of heterogeneous, largely siliceous deposits laid down in the Tertiary period. The entire country is dissected by ground and terminal moraines, overwash sediments, and beds of alluvial material.

The mountain topography of Switzerland considerably facilitates the task of soil and forest classification. On the basis of vertical zonality and the geologic origin of the parent soil material, the area may be divided into seven ecological provinces, as outlined in Figure 10–35 and Table 10–1. A description of the principal soil types and corresponding climax forest vegetation follows (Pallmann *et al.*, 1949; Leibundgut, 1951).

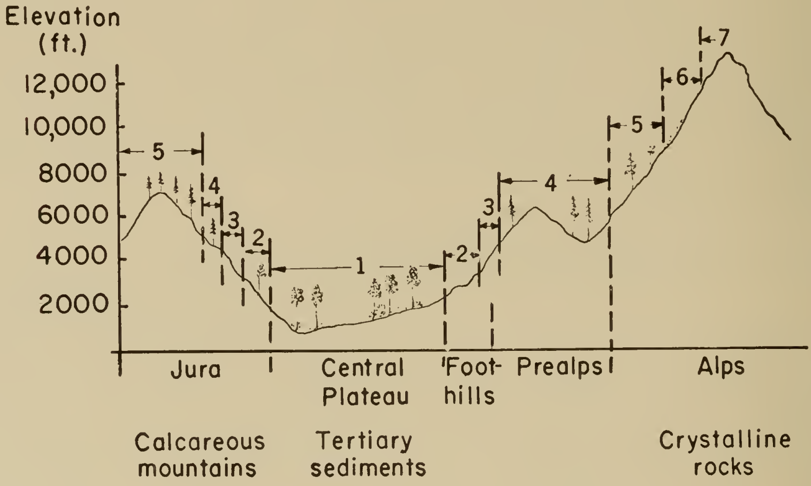


FIG. 10–35. Distribution of genetic soil groups of Switzerland in relation to altitude and geologic substrata: (1) brownearths; (2) brownearths, podzolized brownearths, and rendzinas; (3 and 4) podzolized brownearths, podzolic soils, and rendzinas; (5) podzols, skeletal and raw humus rendzinas; (6) podzols, raw humus rendzinas, and alpine sward soils; (7) lithosols.

Brownearths. These fine-textured and humus-enriched soils have a stable profile morphology and a very high productive potential. In all probability it was a soil of this type upon which the enraptured Jean Jacques Rousseau bestowed his kisses when he crossed the Swiss border.

Although most soils of the brownearth group are taken up by agricultural use, the remaining autochthonous forest cover falls into two major divisions: oak-hornbeam type and ash-maple type.

The oak-hornbeam stands occupy the well-drained areas and in addition to their main constituents, include ash, elm, and cherry. The rich understory of shrubs is dominated by choke cherry and black elderberry. The ground-cover vegetation is characterized by occurrence of *Arum maculatum, Pulmonaria officianalis,* and *An-*

TABLE 10–1

Schematic Outline of the Major Soil-Forest Associations of Switzerland

Ecological regions and altitude	Soil types	Vegetative cover types
1. Central Swiss Plateau; 1000 to 2100 ft.	Brownearths on mixed tertiary sediments and moraines; gley-brownearths, alluvial deposits	Mixed hardwood stands with predominance of oak and hornbeam or ash and maple; *Querceto-Carpinetum; Acereto-Fraxinetum* and *Cariceto-Fraxinetum* types
2. Lower foothills; 1800 to 3300 ft.	Brownearths and podzolized brownearths on moraines and mixed sediments; rendzinas on limestone	Mixed hardwood stands with admixture or predominance of beech; pure beech stands; *Fagetum* associations. Intrusions of Scotch pine
3. Upper foothills; 2400 to 4200 ft.	Podzolized brownearths and podzolic soils on mixed sediments; rendzinas on limestone	Mixed stands of beech, fir and spruce; *Abieto-Fagetum* and *Abietum* types
4. Montane forests; 3600 to 5200 ft.	Podzolized soils on igneous rocks and colluvial deposits; rendzinas on limestone	Spruce with admixture of fir; *Piceetum montanum* type. Intrusions of mountain pine
5. Subalpine forests; 5200 to 7400 ft.	Podzols on igneous rocks and moraines; skeletal and raw humus rendzinas	Spruce of *Piceetum subalpinum* and *Hylocomieto-Piceetum* types; larch and cembra pine of *Rhodoreto-Vaccinietum* type
6. Alpine meadows; 6200 to 10,000 ft.	Podzols, rendzinas, and alpine sward soils, largely on skeletal substrata and deposits of recent glaciation	Heath shrubs, alpine grasses and herbs; *Rhodoreto-Vaccinietum extrasilvaticum* and *Alpinetum* types
7. High Alps; 10,000 to 14,000 ft.	Lithosols; ice and snow	Barrens; *Lichenetum* and *Nudum* types

gelica silvestris. The current annual increment of stands approaches 600 bf or about 1½ cords per acre, the rapid rate of growth being maintained by frequent harvesting of mature trees.

On brownearth soils influenced by seepage or extended capillary fringe, the oak stands are replaced by mixed forests of exacting hardwoods: maple, ash, and elm. These stands spare little light for the development of a shrub understory but are accompanied by a luxuriant association of herbaceous plants, distinguished by the presence of *Allium ursinum* and *Aegopodium podagrarium.* Because of the compacted structure of stands, their total volume is usually higher than that of the oak forest but there is only slight difference in the current increment of the two types.

Brownearth gley soils. The hardwood stands occupying these soils of plateaus form ecological equivalents of the meadow forests commonly found on areas subject to overflow and underlain by well-oxygenated ground water. This similarity is effected by the seepage and surface runoff which provide the upland soils with a generous supply of both moisture and nutrients.

The forest cover is composed of nearly pure ash accompanied by vigorous herbaceous vegetation of *Impatiens parviflora, Equisetum silvaticum, Carex* spp., grasses, and ferns. The current increment at times exceeds 700 bf per acre.

On areas underlain by poorly oxygenated subterranean water, forest cover is formed by glutinuous alder whose yields vary from 15 Mbf to a few cords per acre, depending upon degree of stagnation.

Podzolized brownearths. This term refers to soils which exhibit a translocation of iron and aluminum sesquioxides. This process is caused either by the cold and humid environment of higher altitudes or by artificially established plantations of spruce and other podzol-forming species. In the former case the expression "podzolized brownearths" is obviously speculative and ambiguous, for podzolic soils may be formed without a preliminary stage of sesquioxidic equilibrium. From an ecological viewpoint there is no criterion which separates podzolized brownearths of central Europe from podzolic or mildly podzolized soils of Eurasia and America. As it is true throughout the world, these soils support largely mixed hardwood-coniferous stands or stands dominated by deciduous species that have podzol-forming tendencies, notably beech.

Depending on the altitude and exposure, the forest cover of Swiss podzolic soils is formed by beech, beech with maple and ash, or beech with varying admixtures of spruce and fir. In places of somewhat impeded drainage, fir nearly eliminates hardwood species. The herbaceous vegetation of this broad "Fagetum" zone varies considerably (Braun-Blanquet, 1951) but is characterized by the presence of *Sanicula europea, Asperula odorata, Cardamine* spp., *Elymus europaeus*, and *Maianthemum bifolium.* Honeysuckle, gooseberries, and elderberries occur sporadically. Opening of the canopy usually results in the suppression of the ground-cover vegetation by abundant beech reproduction.

The podzolic soils or podzolized brownearths are among the most important soil types of the Swiss silviculture. The yields of mixed hardwood-coniferous stands may be as high as 60 Mbf per acre; the current increment for the entire soil types varies between 300 and 700 bf per acre per year.

Podzols. Because of fertile substrata, or some other condition, Switzerland thus far has escaped the epidemic of "soil sickness," a severe podzolization brought about by plantations of pure conifers. The Swiss podzols are, as a rule, natural products of the cold and humid environment of high elevations between 5000 and 9000 feet. On siliceous substrata of fairly level topography, podzols are quite comparable to those found on the boreal plains of Europe and America. However, the occurrence of stonelike cemented "Ortsteins" is an exception rather than the rule.

The predominant forest cover consists of pure spruce lacking understory of shrubs. The ground-cover vegetation is dominated by mosses, particularly *Hylocomium splendens* and *Dicranum scoparium.* The dense stands of spruce attain the high yields of 70 Mbf per acre; the current increment approaches 800 bf.

With an increase in elevation and intensified podzolization, the ground cover is enriched in *Lycopodium annotinum, Vaccinium myrtillus,* and *Pyrola* spp., and the yields gradually decrease to 20 Mbf per acre. On porous skeletal substrata the podzolization is suppressed by a vigorous growth of *Calamagrostis villosa,* which forms a layer of dense sod.

At high altitudes the spruce is replaced by larch and cembra pine with their ground-cover associates: *Rhododendron ferrugineum, Vaccinium myrtillus,* and other Ericaceae. These stands usually yield less than 12 Mbf per acre and provide a very low current increment of ⅓ cord per year.

Gley-podzols. On plateaus and in basins with impervious substrata podzolized soils are underlain by a waterlogged gley horizon and develop a thick layer of saprogenous raw humus resembling peat. A similar effect may be produced by impeded seepage or accumulation of vadose water. Most of these soils are occupied by spruce with a ground cover of sedges, reeds, mosses, and heath plants. The growth of trees is usually depressed by insufficient oxygenation and a retarded decomposition of organic remains; the natural regeneration is hindered by competing vegetation. This type occupies only a small fraction of the total forested area.

Rendzinas. These soils of lime-bearing substrata are found predominantly in the Jura Mountains. Their morphology and forest vegetation vary greatly, depending upon the altitude and the nature of calcareous rock.

In the region of brownearth, the rendzinas are characterized by a deep mull layer of incorporated humus and at times are not readily distinguishable from the brownearths. A high percentage of beech and subsequent reduction of oak is one outstanding feature of these soils. At higher altitudes, calcareous substrata tend to moderate podzolization and thereby extend the altitudinal boundary of the hardwood or beech-fir forests. Near the edge of the spruce zone rendzinas support mixed beech-fir-spruce stands that attain the record yield of over 70 Mbf per acre and have an enormously high current increment of 1 Mbf per year.

In subalpine regions, between 5000 and 7000 feet, rendzinas often acquire a thick layer of raw humus and support stands of spruce with ground cover of *Hylocomium* and other "acidophilous" plants. In spite of the apparently unfavorable soil conditions, the yields at times approach 20 Mbf per acre. On steep slopes the calcareous rocklands or "skeletal rendzinas" support parklike stands of spruce, pine, and juniper.

Alpine swards. At the elevations of 6000 to 7000 feet trees reach their natural limit of distribution and give way to alpine meadows which develop prairie-like sward soils with a deep and fertile layer of incorporated humus. Some of these soils owe their origin to deforestation and grazing.

In the lower limits the alpine sward soils are fringed by sporadic open stands of spruce, larch, and mugho pine or by clumps of *Juniperus communis, Rhododendron ferrugineum, Vaccinium* spp., and *Empetrum nigrum.* The last plant serves as a link connecting such geographically distant but ecologically close regions as the Swiss Alps, Fenno-Scandia, and Alaska. At an elevation of about 10,000 feet alpine swards grade into "boulder fields," lichen-covered rock outcrops, and eternal snow (Fig. 10–36).

FIG. 10–36. High mountain landscape of Switzerland. (Dr. H. Leibundgut, School of Forestry, Zürich.)

SOIL-FOREST ZONES OF THE ROCKY MOUNTAINS

> *I could distinctly hear the varying tones of individual trees—spruce, and fir, and pine, and leafless oak . . . Each was expressing itself in its own way, singing its own song, and making its own peculiar gestures, manifesting a richness of variety to be found in no other forest I have yet seen.* —John Muir

The Rocky Mountains extend from border to border of the entire North American continent and from sea level to an altitude of about 15,000 feet. This great range exhibits an enormously wide gamut of zonal soil groups and floristic formations delineated by the deserts at the foothills and alpine meadows or skeletal barrens crowning the mountain tops.

The system is young in a geological sense and the mountains are sharply dissected. The ranges tend to be aligned in a north-south direction and serve as barriers intercepting the moisture-bearing winds from the Pacific Ocean. Both of these features, together with the high elevation, are responsible for the drastic differences in climatic conditions which are encountered at a distance of several miles in either a vertical or an east-west direction. As a result, the effect of climatic factors usually overshadows that of geologic substratum and differentiates both vegetation and soils into distinct climatic-zonal groups. The zonal associations of forest cover are characterized by the predominance of different tree species and are classified into "types," such as "piñon-juniper type," "Douglas fir type," and "spruce-fir type" (Shantz and Zon, 1924). Each of these broad formations may include a number of soil-forest units or floristic types twice as great as that found in Finland. However, the scarcity of available information on soils and ground-cover vegetation of the Rocky Mountains permits only a general outline of the broad divisions which at present constitute the major silvicultural importance.

The effect of elevation and exposure on the annual rainfall and the distribution of forest trees in the neighboring Sierra Nevada Mountains (Fig. 10–37) is very instructively illustrated by Show and Kotok (1929).

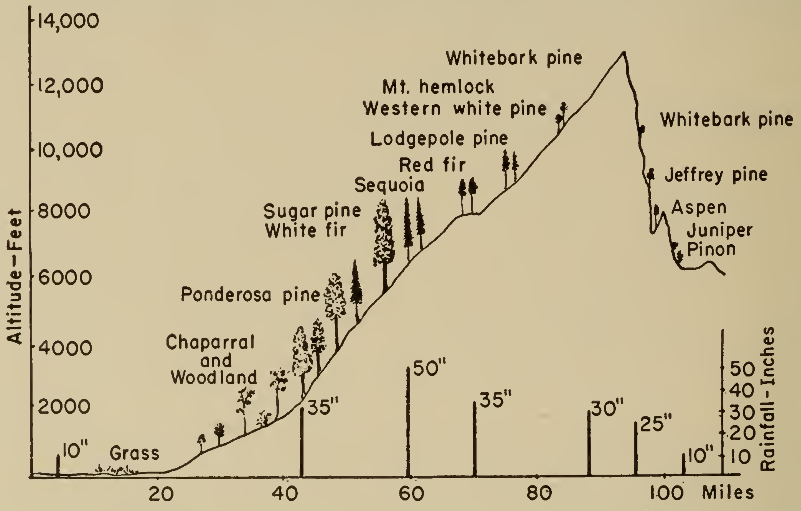


Fig. 10–37. Distribution of trees in the Sierra Nevada as influenced by altitude, exposure, and precipitation. (After Show and Kotok, 1929.)

Dry woodland types. The lowest of the timber zones with an annual rainfall of less than 20 inches is occupied by the chaparral and piñon-juniper types, occurring on shallow and stony semidesert soils.

The chaparral is composed mainly of scrub oak species, mountain mahogany, juneberry, and a number of shrubs. The stands have a low density and the trees are brushy and stunted. The ground is covered with sagebrush and short grass. This type is widely distributed but has little commercial value except as a source of fuel. It is important for watershed protection.

The piñon-juniper type consists of several species of juniper and two species of piñon, *Pinus edulis* and *Pinus monophylla*. At the higher altitudes there occur scrub oaks and dwarf forms of Douglas fir and ponderosa pine. The low stocking of this type permits the growth of herbaceous vegetation and low shrubs. The stands are usually uneven-aged, of slow growth and poor form. The piñon-juniper type covers a large area and is a source of fuel, posts, and mine timber.

Ponderosa pine type. This type borders the dry woodland zone, extending in the southern part of the Rockies to an elevation of 8000 feet. The rainfall fluctuates between 20 and 25 inches. The growing season is short and dry, and temperatures of 110° F. occur quite frequently. The brown or grayish-brown soils of semidesert types are often shallow and stony, very low in organic matter, and at times of a neutral or an alkaline reaction. The surface layers are usually of sandy texture and grade into a heavier *B* horizon. The forest litter as a rule is absent, but in places piles of dry cones accumulate at the bases of the trees.

The stands of lower elevations are composed of pure ponderosa pine. At higher altitudes a certain portion of the stand is made up of Douglas fir. The stands are parklike with a ground cover of grass and other herbaceous vegetation. They resemble somewhat the longleaf forests of the Atlantic Coastal Plain. The trees, however, attain good form and size (Fig. 10–38). After forest fire or logging, the area is usually reoccupied by the ponderosa pine, which acts as both a climax and a pioneer species. Because of the wide distribution, value of wood, and comparative ease of logging, this type has a high commercial importance.

Douglas fir type. This type occurs above the ponderosa-pine belt and extends occasionally to an elevation of nearly 10,000 feet. Precipitation varies between 25 and 30 inches, the larger share of which is in the form of snow. Prolonged periods of drought occur in the spring and fall. The melanized soils of this belt exhibit rhizogenous and microbiotic mull layers and are usually well supplied with nutrients. However, they are often shallow and have a low water-retaining capacity.

Douglas fir is associated with ponderosa pine and limber pine at lower altitudes and with Engelmann spruce and white fir in the upper part of the zone. The dominant trees at times attain a diameter

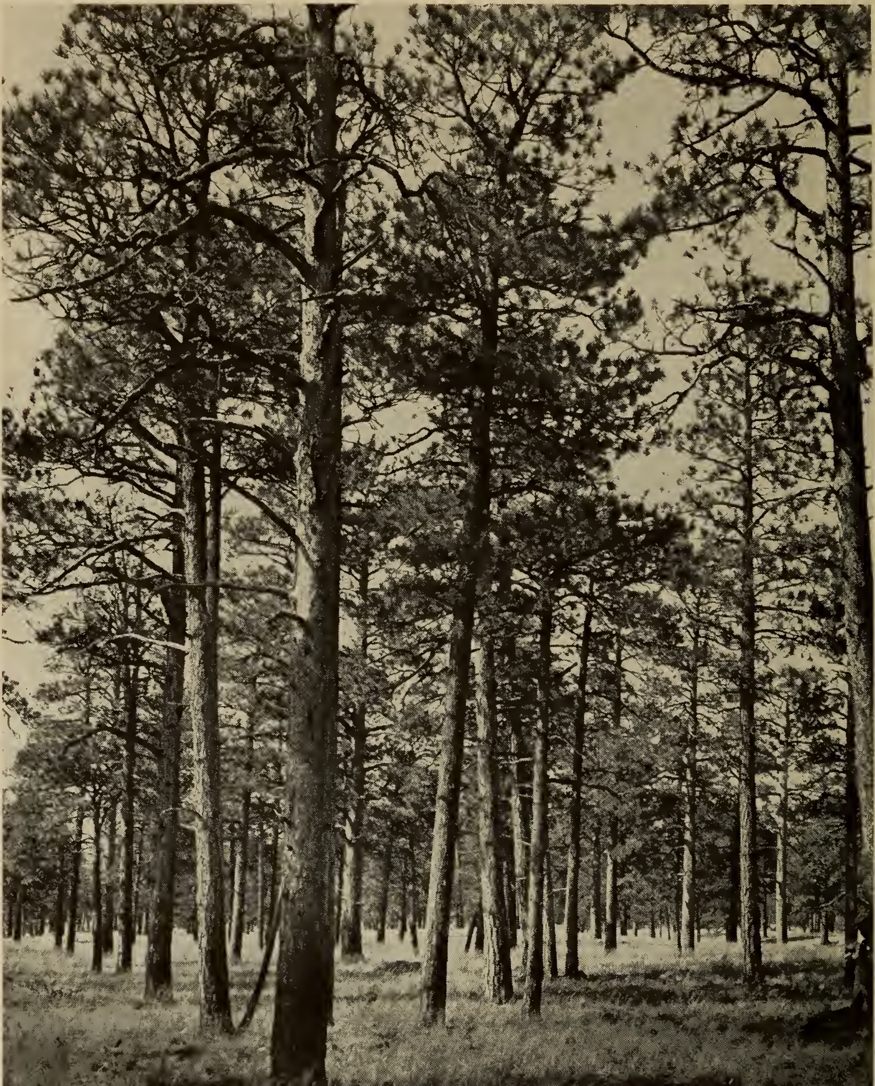


Fig. 10–38. Stand of ponderosa pine on a sod-covered soil of Arizona. (U. S. Forest Service.)

of over 15 feet and a height exceeding 250 feet (Fig. 10–39). The logged or burned over areas are usually invaded by aspen or lodgepole pine.

Lodgepole pine type. Lodgepole pine has a very wide ecological amplitude. It tolerates great extremes of temperature, is fairly

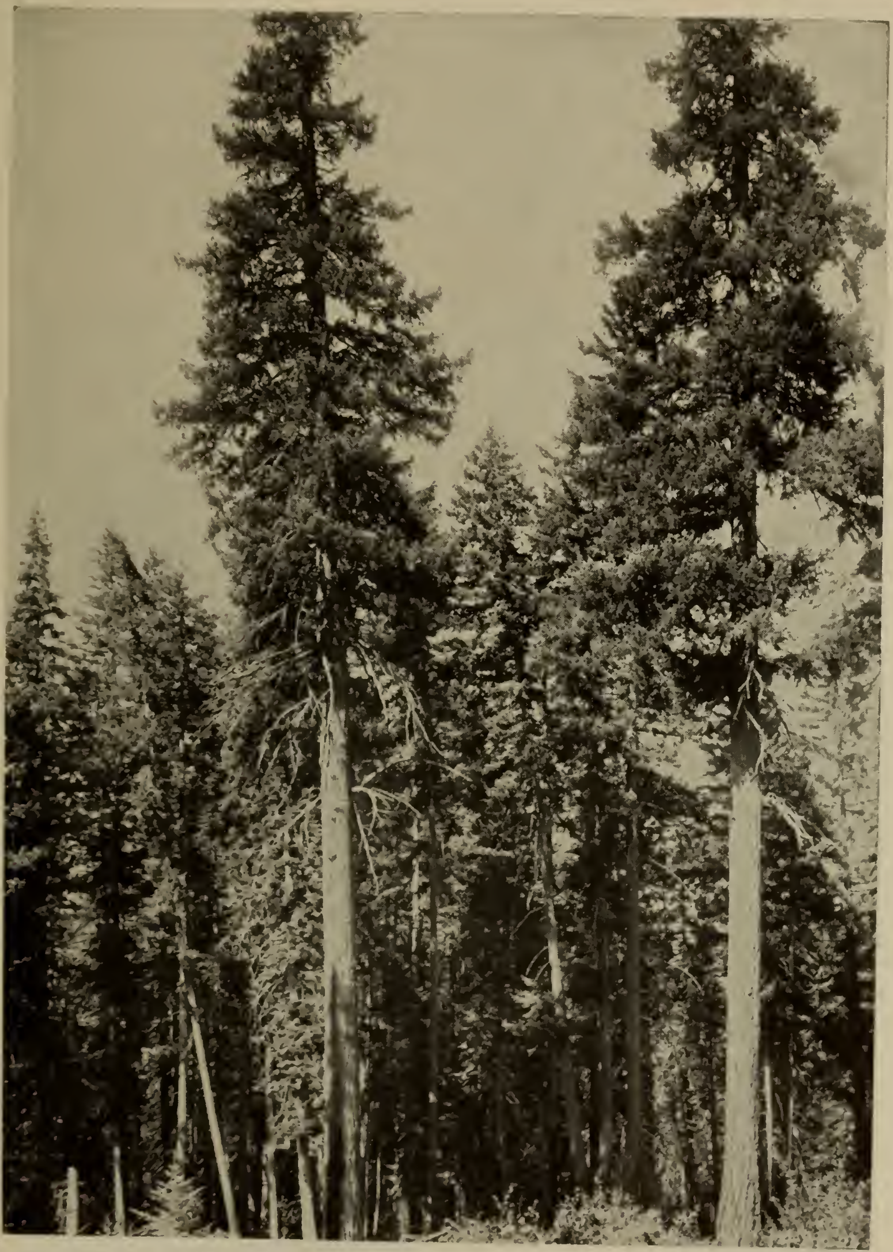


FIG. 10–39. Stand of Douglas fir; forest cover of primary importance in the middle altitudes of the western mountain ranges. (U. S. Forest Service.)

resistant to drought, and has moderate nutrient requirements. The range of this species extends from the ponderosa pine zone to the proximity of the timber line. At the lower elevations the distribution is limited by a rainfall of less than 18 inches. As a rule, lodgepole pine forms pioneer cover which is eventually replaced by either Douglas fir or Engelmann spruce. The opening of the cones by fire is largely responsible for the occurrence of extremely dense, even-aged pioneer stands of lodgepole pine on burned-over areas of a great variety of soil types.

Spruce-fir type. This is the timber-line type, extending to an elevation of about 12,000 feet, where it grades into the alpine meadows. The annual precipitation is about 30 inches. The average temperature of the growing season slightly exceeds 50° F. The length of the growing season may be less than three months. The shallow and stony soils of the mountain podzol type are covered with a layer of raw humus. The soil profile shows a podzolized zone, up to 3 inches in thickness, and a slightly developed horizon of deposition.

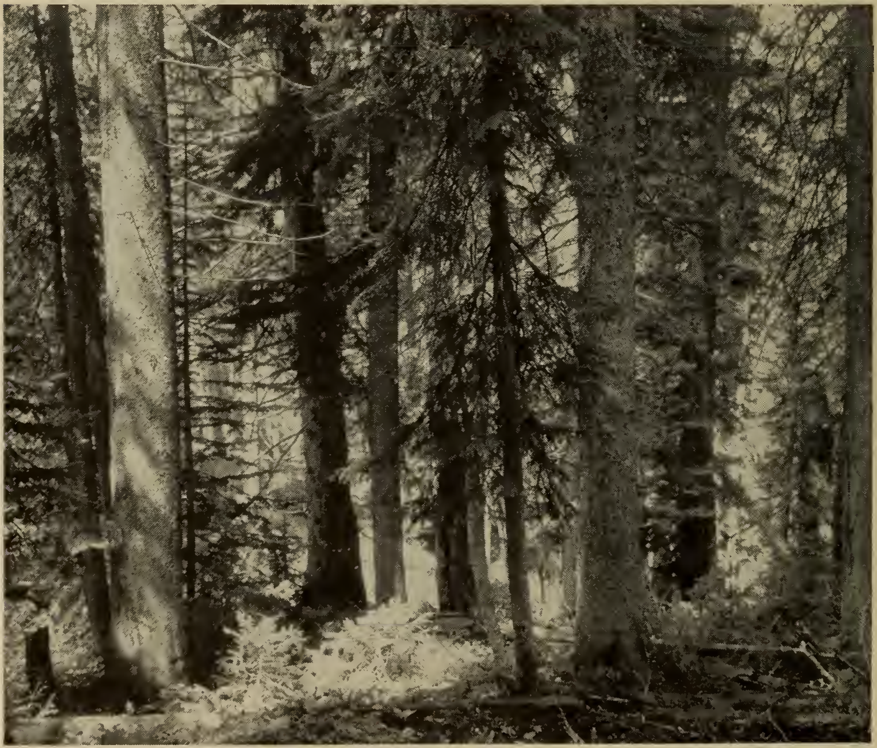


Fig. 10–40. Virgin stand of Engelmann spruce on a raw humus soil of a mountain podzol type. (U. S. Forest Service.)

The forest is composed of Engelmann spruce with varying amounts of lodgepole pine, limber pine, bristle-cone pine, Douglas fir, cork-bark fir, and alpine fir (Fig. 10–40). The latter two species are the chief associates, especially on the cooler and more moist sites. The forest stands are uneven-aged and well-stocked. The mature trees reach a diameter of 30 inches. On level areas along the streams and at higher altitudes, the forest cover is usually replaced by mountain meadows with sporadic groups of mountain hemlock or alpine fir (Fig. 10–41).

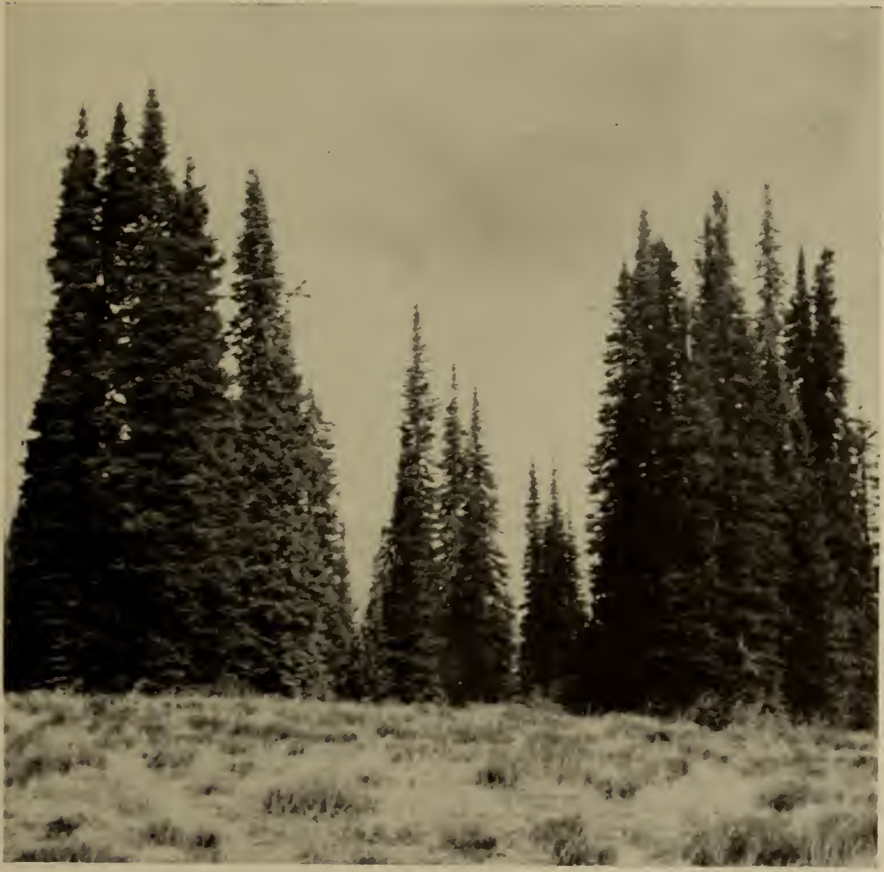
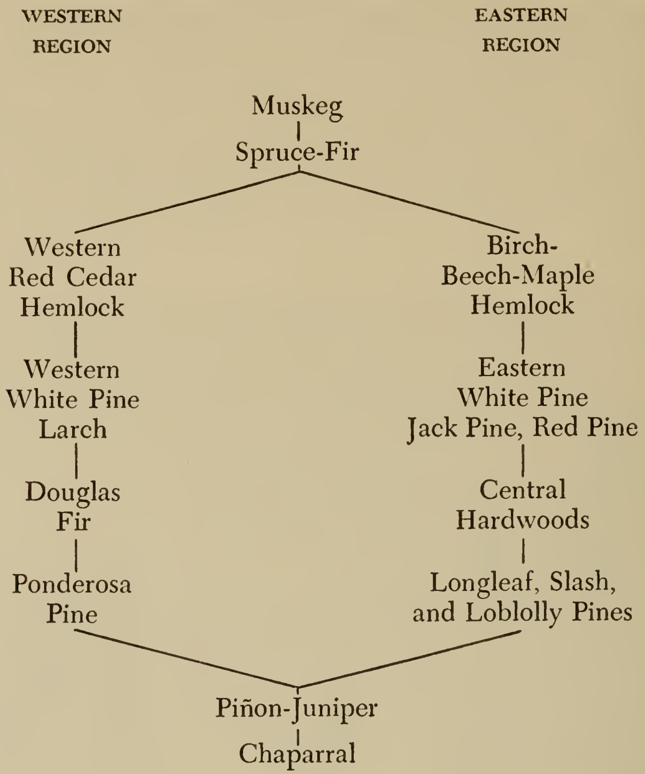


FIG. 10–41. Alpine fir on a mountain sward soil of Idaho. (U. S. Forest Service.)

As has been pointed out by Shantz and Zon, there is a close similarity in the development of forests in the western and the eastern portions of North America. This relation, in greatly simplified form, is outlined in the following diagram.



SOIL-FOREST TYPES OF EASTERN MANCHURIA

> *The enormous trunks of Siberian pine and spruce are entwined to the very tops with lianas . . . Among the dark green color of conifers, the eye is caressed by the lighter foliage of ash, walnut, and other deciduous trees.*
>
> —B. A. Ivashkevitch

It would be difficult to find a subject more suitable than this part of Asia to conclude the review of soil-forest relations. Because of its present physiographic conditions and its past history, eastern Manchuria presents an unusual, almost freakish combination of soils and forest cover. Both the genetic pattern of soils and the composition of floristic associations exhibit characteristics of the boreal as well as the subtropical landscapes of Eurasia and North America. An American forester is likely to detect a remarkable similarity between soil-forest units of Manchuria and those of the Great Lakes region and the Atlantic Coastal Plain of the United States.

The climate of eastern Manchuria, as a whole, may be considered as transitional between continental and oceanic. The outstanding characteristics of the region are: cold winters with little snow, warm summers with abundant rainfall, high relative humidity, and prevalence of western winds in winter and eastern winds in summer. The elevation in places approaches 5000 feet, and the climatic conditions vary greatly with altitude and exposure. The geologic substratum is composed largely of granite and related feldspathic rocks.

The podzolic soils of the higher altitudes grade into nut-structured gray forest soils of the lower slopes and young alluvial soils of the river valleys. The color of some soils suggests the past influence of the laterization process. A description of the principal soil-forest types, as reported by Ivashkevitch (1916), follows.

Coniferous-hardwood type of high elevations. This type occurs on shallow regolithic soils developed from crystalline rocks at altitudes from 2500 to 4200 feet. The horizon with incorporated humus varies in thickness from 2 to 5 inches, and often grades into a leached layer, which in turn is underlain by slightly weathered parent material. The stands are composed of *Picea ajanensis* and *Abies nephrolepis* with some *Betula plotyphylla, Acer manshuricum, Tilia manshurica,* and *Ulmus montana. Pinus manshurica* occurs sporadically, and the fir often forms an understory. The stands are abnormally dense, but the height of the trees usually does not exceed 60 feet. Ground cover consists of mosses and *Oxalis acetosella.*

Coniferous-hardwood type of lower slopes. The occurrence of this association is limited to altitudes below 2500 feet. The stands of best development are found on slopes not exceeding 15 degrees. The loam soils are largely of overwash origin and are somewhat podzolized. The humus-enriched horizon reaches a thickness of 8 inches and is underlain by a faintly differentiated, yellowish-gray A_2B horizon. The predominant member of the forest cover, *Picea ajanensis,* is accompanied by hardwoods and *Pinus manshurica.* The understory includes *Corylus manshurica, Acer manshuricum,* and *Tilia manshurica.* The ground cover is characterized by *Oxalis acetosella, Maianthemum bifolium* and *Lycopodium* spp.

Pine-hardwood type of lower slopes. This type is distributed on sandy or sandy loam soils at elevations below 2500 feet. The upper part of this zone is occupied by residual podzolized soils which grade at lower elevations into slightly leached overwash soils exhibiting aggregated *B* horizons. *Pinus manshurica* is the predominant species; *Fraxinum manshurica, Juglans manshurica,* and *Phellodendron amurense* are the most important associates. The shrub layer is composed of dense *Corylus manshurica.* The stands are penetrated by abundant lianas, particularly *Vitis amurensis, Schezandra chinensis,* and *Actinidia* spp. The rich ground-cover vegetation is characterized by *Alcrophora lilifolia, Paris obovata, Arena Schelliana,* and *Vicia baicalensis.*

Coniferous-hardwood type of valleys. This type occurs on gentle slopes of the valleys covered by deep, dark-gray forest loams or silt loams resembling prairie-forest soils. The friable litter rests on a deep layer of crumb-mull or grain-mull humus. The leaching is masked by infiltrated humates. Ground water usually occurs at a depth of about 4 feet, but the aggregated upper part of the soil profile is adequately aerated. The forest association is very complex and includes pine, spruce, fir, and numerous hardwoods. The outstanding characteristic of this type is the presence of apple, cherry, alder, and rock elm. The understory is dense, and lianas reach their greatest development, so this type may truly be called impassable. The herbaceous vegetation is also luxuriant and includes: *Paris obovata, Maianthemum bifolium, Convallaria majalis, Polygonatum multiflorum, Filipendula purpurea, Impatiens noli tangere, Aquilegia oxysepala, Thalictrum, Aconitum, Viola, Angelica dahurica, Solidago virga aurea, Dianthus chinensis, Equisetum* and *Lycopodium* spp., and numerous ferns, including *Adiantum pedatum,* the beauty of American deciduous forests. Because of the high percentage of hardwood species, the yields are somewhat lower than those of higher elevations. Pine shows a rather high percentage of cull.

River-bottom hardwoods. This type is confined to areas subject to overflow. The deep alluvial soils support chiefly elm, walnut, and philodendron. Pine and other conifers occur sporadically. The dense understory is dominated by *Syringa amurensis.* The trees seldom reach a height of more than 60 feet and are often infested with heart rot. The ground cover is characterized by the presence of ferns, grasses, and sedges.

Coniferous swamps. This type occurs on moss peat bogs. The stands are ordinarily 70 per cent larch, 20 per cent Siberian spruce, and 10 per cent pine and birch. The understory includes spruce, birch, and suppressed larch. The density of the stands seldom exceeds 70 per cent. Virgin stands reach a height of 80 feet. The ground cover is made up of *Sphagnum* spp., *Eriophorum,* and

Equisetum. The presence of larch in these stagnant bogs of warm valleys is rather puzzling, since this tree ordinarily occurs on the rocky ridges of Asiatic mountains at elevations as high as 5000 feet. Apparently the low temperature of the moss peat accounts for the fact that other species cannot compete with larch on these sites.

II

SOIL SCIENCE AND SILVICULTURE

What greater folly can be imagined than to call gems, silver, and gold noble, and earth and dirt base? For do not these persons consider that, if there were as great a scarcity of earth as there is of jewels and precious metals, there would be no king who would not gladly give a heap of diamonds and rubies and many ingots of gold to purchase only so much earth as would suffice to plant a jessamine in a little pot or to set a tangerine in it, that he might see it sprout, grow up, and bring forth such goodly leaves, fragrant flowers, and delicate fruit?

—Galileo

11

I take it upon me to say, that to be a good husbandman, it is necessary to be a good chymist. Chymistry will teach him the best way to prepare nourishment for his respective crops, and, in the most wonderful manner will expose the hidden things of nature to his view.

—Dr. A. Hunter,
Georgical Essays, 1777

Management of nursery soils

Scope of nursery soil management. Forest nurseries are offsprings of necessity. In the early days of silviculture, foresters tried to imitate farmer's practices and broadcast seed on cut-over lands, but the results failed to fulfill the expectations. In about nine out of ten cases, the seed was devoured by birds and rodents or destroyed by parasitic fungi; the seedlings destined to open their foliage were killed by drought, sunscald, or frost, or were suppressed by competing vegetation. To preclude these losses the seedlings are first raised in protected nursery areas where favorable growth conditions are maintained by cultivation, artificial watering, application of fertilizers, use of cover crops, and control of parasitic organisms. The main objective of all these measures is to achieve the production of vigorous and disease-free planting stock, and thus to reduce to a minimum the failure or eventual deterioration of plantations.

SELECTION OF NURSERY SITES

A management unit in European forests seldom exceeds 10,000 acres. Therefore, with a common rotation of eighty years the area to be reforested annually is 125 acres. The planting of this area requires about 250,000 seedlings which can be produced annually in a nursery less than one acre in size. This planting stock can be successfully raised in a **temporary nursery**, located on a recently cut-over area and maintained as long as the natural soil fertility is not exhausted. The practice of temporary nurseries has many advantages, but it is not suitable to a large-scale American reforestation program. The need for millions of seedlings, as well as the high cost of labor, call for the employment of mechanized equipment, the full utilization of which is possible only in well organized **permanent nurseries** (Fig. 11–1).

The establishment of a permanent nursery requires a large investment for grading, fencing, irrigation system, cold storage house, garages, and buildings for the office, packing of stock, and machinery. Therefore, a permanent nursery cannot be moved to another place without a loss of many thousands of dollars. On the other hand, a nursery established on an unsatisfactory site raises the cost of stock production and often delivers inferior planting material.

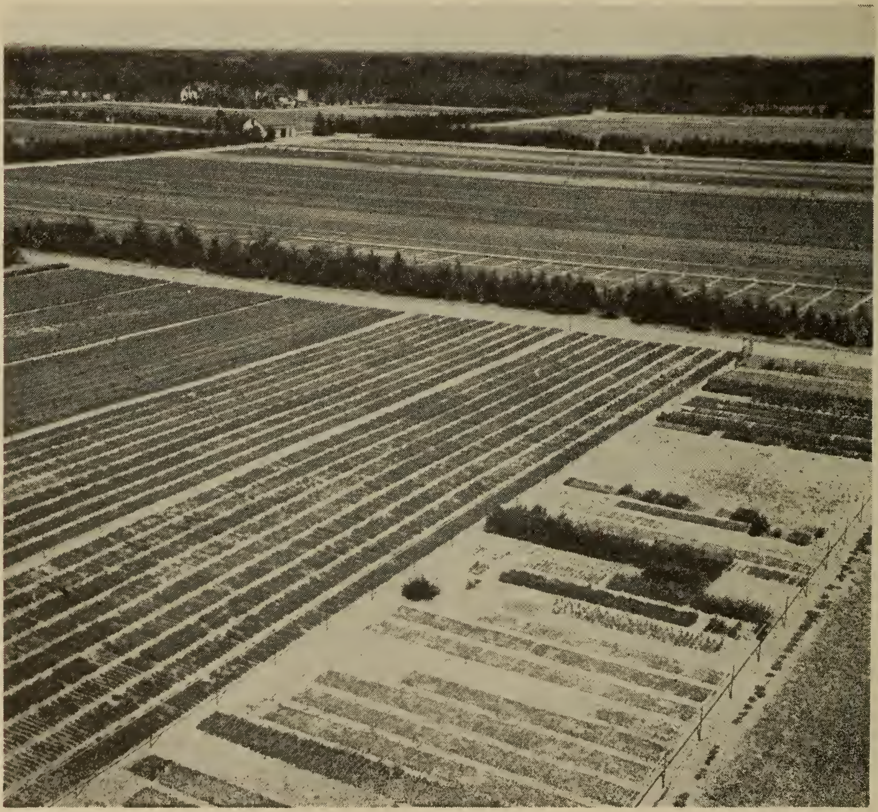


Fig. 11–1. Bird's eye view of a permanent forest nursery producing annually fifteen million seedlings. (Wisconsin Conservation Department.)

The person who is appointed to select the nursery site should bear in mind that he will be held responsible for the difficulties which may eventually arise in growing stock. For this reason he should invite the advice of experienced nurserymen and specialists in forestry, soils, entomology, and plant pathology. A written statement by these technicians is always more valuable than oral suggestions. Investigation should embrace the physiographic factors, properties of the soil, biological aspects, and economic conditions. The following discussion covers the important points to be considered.

Climatic and topographic factors. Areas exposed to extreme temperatures, especially early and late frosts, should be carefully avoided. In cold regions attempts should be made to locate the nursery in the proximity of large bodies of water which moderate climatic extremes. In hilly country, the northern exposure is usually preferable because of reduced danger of stock injury by late spring frosts. The length of the growing season and other climatic conditions of the nursery site should not greatly differ from those of the region to be reforested. This is particularly true in high mountains where the stock may be actively growing in the valley nursery while the soil of planting sites at high elevations is still frozen. The topography and the location of neighboring forest stands should allow for the drainage of the cold air and thus preclude frost injury. If possible the area should not be exposed to strong winds which may damage seedlings by blowing sand and by excessive evaporation during snowless cold periods.

As a rule, a level area is most desirable, but a gentle slope may be beneficial for fine-textured soils because of a better surface drainage. Slopes of considerable gradient are subject to erosion, and the denudation of seedbeds causes difficulties even in nurseries with soil of a sandy texture. Moreover, inclined areas cause highly undesirable translocation of soluble fertilizer salts. Water accumulating in depressions, no matter how slight, causes complete destruction of nursery stock. Slopes of moderate gradient and small rough areas may be leveled by terracing and grading, but these operations usually expose the infertile subsoil and require considerable expense. Care should be taken not to locate the nursery within a zone subject to inundation.

Soil factors. Soils of recently cleared areas with undecomposed litter and incorporated humus are much more desirable than soils of cultivated, burned-over, or sodded lands. The soil should be at least 4 feet deep and should not exhibit radical differences in the composition of its genetical horizons; soils including impervious interlayers of shale, claypans, hardpans, iron concretions, calcareous substrata, or mottled gley layers should be especially avoided. The undesirable features of the deeper soil layers will become more pronounced if the surface soil is partly removed in leveling the area. The minimum allowable depth of the ground water table varies between 4 and 5 feet. The dryness of the surface soil in summer or fall may be grossly misleading as to the position of the ground water, and a thorough examination of the soil profile is imperative.

Sandy loams, containing from 15 to 20 per cent of silt and clay particles, are preferable. Lighter soils may be improved by the addition of organic matter or, in some cases, clay. Soils high in colloids are undesirable because of difficulties in cultivation, weeding, control of parasites, and adjustment of reaction. In cold regions heavy soils remain frozen late in the spring, and plant roots may be seriously injured while the seedlings are lifted. Also, on heavy soils the seedlings often suffer from heaving or freezing out. The improvement of heavy soils by the addition of sand is seldom practicable. Special attention should be given to the content of gravel and stones imbedded in the upper 18 inches of soil, since this skeletal material will greatly interfere with nursery operations.

The optimum reaction for most tree species is between pH 5.0 and 6.0. Soils of a lower pH may have a low content of available nutrients; soils of a higher pH encourage the invasion of fungus diseases. Alkaline soils usually present many more difficulties than do strongly acid soils.

An approximate **minimum** content of nutrients in the upper 6-inch layer of the soil may be indicated as follows: total nitrogen—0.07 per cent; available phosphorus pentoxide (P_2O_5)—25 pounds per acre; available potassium (K_2O)—100 pounds per acre; exchangeable calcium—1.5 m.e. per 100 g.; and exchangeable magnesium—0.5 m.e. per 100 g. The content of nutrients is not too greatly important, for it can always be adjusted by the addition of fertilizers. It is imperative to ascertain, however, that the soil does not contain soluble salts, carbonates, or any toxic substances in high concentrations. If the area had been used before as a nursery, orchard, or for raising truck crops, it is necessary to determine the content of arsenic which might have been introduced for the control of parasitic insects.

A nursery soil should have at least 2 per cent of organic matter in the upper 6-inch layer. In most instances the productivity of a permanent nursery sooner or later will become dependent upon the supply of organic matter to be used for the improvement of the physical condition of soil, as a source of nitrogen, and as a carrier of fertilizers. Therefore, it is essential that a suitable deposit of peat is located within a reasonable distance.

Biotic factors. The possible occurrence of parasitic fungi and insects should be investigated in the field and by greenhouse tests. The presence of parasites is to be expected in most soils of abandoned fields. It should be made certain that the soil contains mycorrhizal fungi; in doubtful cases this should be verified by greenhouse trials. The biological activity of the soil can usually be improved by the applications of litter or leaf mold from productive forest stands. Such stands should be located in the vicinity. If possible, areas supporting persistent weeds should be avoided.

Economic factors. To decrease the cost of transportation the nursery should be located as near as possible to the center of the planting region. The possible expansion of the reforestation program must be considered and the eventual enlargement of the nursery ensured by the purchase of sufficient acreage at the start.

The supply of water for irrigation and for drinking must be carefully examined and subjected to chemical and bacteriological analyses. The site for the pumphouse should be located and the length of water pipes estimated for the determination of the cost of the irrigation system. Special attention must be given to the condition of roads in the spring; "mudholes" or "swollen creeks" may cause embarrassing delays in delivering seedlings during the planting season. It is important that power and telephone lines be in the proximity of the nursery site. Since the efficient management of a nursery demands the presence of a nursery superintendent and his assistants almost constantly, conditions should allow for the permanent location of these officers and their families in the vicinity. Housing and an accessible populated center and school are of primary importance. The availability of labor should also be taken into account.

PREPARATION OF SEEDBEDS

If the area selected for a nursery site supports a forest stand, it is necessary to make an exact plan of the location of seedbeds, roads, and buildings before clearing. This must be done in order to preserve in proper places strips of trees and shrubs which would serve as windbreaks or hedges. After the timber is logged, the slash is either removed and allowed to decay in compost heaps, or it is burned in small piles. The stumps are pulled with a tractor and used for fuel; stump holes are filled with soil. The dry season is best suited for pulling the stumps as the soil is easily separated from the roots then. The cleared land is plowed, disked and harrowed, or rototilled, and the seedbeds are prepared. The cultivation or rototilling of the soil is particularly urgent on sites infested with white grubs or weeds.

Areas of irregular topography must be graded or terraced with a scraper-tractor unit. In grading, the fertile topsoil is moved to one side, the sterile subsoil is leveled, and the topsoil is then distributed uniformly over the surface (Fig. 11–2). A contour map or a series of level traverses is essential for the calculation of the cut and fill and the efficient grading or terracing of any extensive area. The utmost care must be taken to grade to a uniform level or slightly inclined surface. In soils with a less pervious substratum, provision should be made for establishing tile drainage.

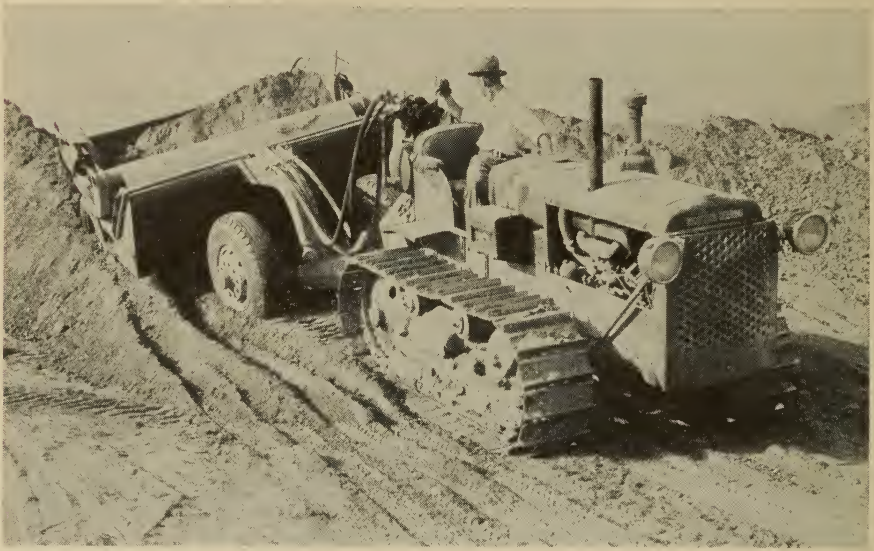


Fig. 11–2. Grading of land, a major operation for establishing a nursery in rolling topography that requires extremely careful performance. (The International Harvester Co.)

The technique of seedbed preparation and seeding is discussed in the comprehensive volume by Toumey and Korstian (1942).

USE OF COMMERCIAL AND NATURAL FERTILIZERS IN FOREST NURSERIES

Regardless of the original fertility of the soil selected for a forest nursery, the content of organic matter and nutrients will be depleted in the course of time because of cultivation, leaching, activity of microorganisms, and nutrition of the seedlings. The fertility of soil may be reestablished in a safe and natural manner by the application of litter or leaf mold from productive forest stands. These materials, however, are seldom available in large quantities, and their procurement is costly. In order to bring the nutrient content of a depleted sandy nursery soil to its original state it may be necessary to apply as much as 50 tons of organic remains per acre. Because of this, the maintenance of nursery soil fertility usually depends upon the use of commercial fertilizers, applied either directly or in combination with natural fertilizing materials. Therefore, one of the first tasks of the nursery soil manager is to become familiar with the composition and effects of different fertilizer salts and the methods of preparation and application of fertilizers—broadcast, in the form of composts, and as solutions.

NITROGEN FERTILIZERS

Sodium nitrate or "Chile saltpeter," $NaNO_3$, occurs as a natural deposit in South America. It is also produced from synthetic nitric acid and sodium carbonate. The refined salt contains about 16 per cent of nitrogen.

Sodium nitrate is soluble in water and readily available to plants. It has special value in nursery soils of a strongly acid reaction, soils treated with biocides or organic remains of a high C/N ratio, and soils supporting stock of upland hardwoods or other nitrate-demanding species.

Continued applications of sodium nitrate may lead to a decrease of soil acidity because of assimilation of the nitrate ion by the plants and accumulation of sodium in the exchange compound as well as in the form of free sodium carbonate. This may be schematically represented by the following equations:

$$NaNO_3 + B \cdot x \rightarrow Na \cdot x + B \cdot NO_3$$

$$2Na \cdot x + H_2O + CO_2 \rightarrow 2H \cdot x + Na_2CO_3$$

The accumulation of sodium is detrimental to seedlings of most species because of a decrease of acidity and because of the direct toxicity of the sodium ion. Therefore the application of sodium nitrate should be limited to cases of urgent necessity. Nitrates should not be applied on seedbeds of conifers subject to damping-off. Adverse soil conditions resulting from the excessive application of sodium nitrate may be corrected by the application of acid fertilizers, particularly ammonium sulfate.

Because nitrates are easily lost through leaching, sodium nitrate is usually applied in a liquid form for immediate consumption. The common rate of application varies from 100 pounds to 200 pounds per acre at a time. After the application the treated beds should be watered rather conservatively so as to prevent leaching of the fertilizer and to avoid anaerobic conditions which would lead to denitrification.

Calcium nitrate or "Norwegian saltpeter," $Ca(NO_3)_2$, is produced from lime water and synthetic nitric oxide. This fertilizer has about 16 per cent nitrogen and is readily soluble in water. It could be used to advantage on strongly acid nursery soils deficient in calcium. However, it is highly deliquescent and expensive. In other respects it is similar to nitrate of soda.

Ammonium sulfate, $(NH_4)_2SO_4$, is a by-product of coke or coal distillation and is also manufactured from ammonia, calcium sulfate, and carbon dioxide. It has about 20 per cent nitrogen. The salt is easily soluble in water and, under favorable conditions, its ammonia is quickly converted into the nitrate form by nitrifying bacteria. This makes the nitrogen in ammonium sulfate available to the plants almost as readily as is that in nitrate fertilizers. A great number of the coniferous species have the ability to utilize ammonia nitrogen without its conversion to the nitrate form. Because the ammonia is energetically adsorbed by the soil colloids and used by plants, the sulfate ion accumulates and produces an acid reaction according to the equation:

$$(NH_4)_2SO_4 + 2H \cdot x \rightarrow 2NH_4 \cdot x + H_2SO_4$$

In most cases an acid reaction is beneficial to the seedlings; hence, ammonium sulfate is, in general, a much more desirable commercial nitrogen fertilizer than sodium or calcium nitrate. This is particularly true when coniferous stock is grown. The acidification of a soil through the application of ammonium sulfate serves in a measure to control parasitic fungi. An especially valuable characteristic of ammonium fertilizers is that the ammonium ion enters the soil exchange compound, where it may be retained for a longer period (Truog, 1938).

Although ammonium sulfate contains more nitrogen per unit than the nitrate fertilizers, it is more stable in the soil and may be applied at a rate as high as 300 pounds per acre. In some cases it is advantageous to combine sulfate of ammonia with sodium nitrate in a ratio determined by soil conditions and composition of stock. Because ammonia is liberated by alkalies, ammonium sulfate should not be mixed with lime, potassium carbonate, wood ashes, or similar basic materials before application. If ammonium sulfate is used continuously, toxic compounds may be formed through the reaction of iron, aluminum, and manganese with the free sulfuric acid produced upon addition of the fertilizer.

Ammonium nitrate, NH_4NO_3, is manufactured synthetically from nitrogen of the air. The pure salt contains 35 per cent nitrogen, of which half is in the form of ammonium and half is in the form of nitrate. This highly concentrated, double salt fertilizer is of special value in liquid treatments. Advances have been made in decreasing the hygroscopicity of ammonium nitrate, thus making it one of the most desirable sources of nitrogen for nursery practice. It leaves neither anion nor cation residue in the soil, is highly soluble, and is perhaps the fastest acting nitrogen fertilizer known. One hundred pounds per acre at a time is a high application of ammonium nitrate.

Calcium cyanamid, $CaCN_2$, is manufactured from calcium carbide through which nitrogen gas is forced at a high temperature. It contains from 20 to 25 per cent nitrogen and breaks down in the soil into ammonia and nitrates:

$$CaCN_2 + 3H_2O \rightarrow CaCO_3 + 2NH_3$$

$$NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$$

In the course of these changes some toxic compounds are formed, and the fertilizer cannot be applied shortly before seeding or planting nursery stock. For this reason calcium cyanamid finds little use in nursery practice.

Urea, $CO(NH_2)_2$, is manufactured by combining ammonia with carbon dioxide under high pressure. It carries 46 per cent nitrogen and for forestry use appears to be either equal or even superior to other sources of nitrogen. It may be utilized by plants to some extent directly, but is mostly used after its conversion to ammonium and nitrate. Urea is readily soluble and subject to leaching, but ammonification considerably reduces the losses. This fertilizer is finding increased use for direct application to nursery soils, as an ingredient of composts, and for treatment of forest plantations. Because urea readily ammonifies in moist soils, the danger of root injury is not excluded.

Uramon consists of crystal urea coated with inert mineral and organic substances for conditioning purposes. It is 42 per cent nitrogen and costs about as much per pound of nitrogen as other low-cost solid nitrogen fertilizers.

Uramite or "Urea-form" is a compound of urea and formaldehyde, assaying 36 to 38 per cent nitrogen. Because it is a slowly soluble nitrogen source, losses by leaching are minimized. In one experiment such losses of uramite were one-tenth of those encountered with urea. This product has an excellent physical condition and is classed as a plastic. It can absorb a high percentage of water without caking. Because uramite contains formaldehyde, it is of value both as a biocide and as a fertilizer.

N-Dure fertilizer (Concentrate 85) is a urea-formaldehyde product which is now undergoing experimental trials. It is a liquid of 25 per cent urea and 60 per cent formaldehyde.

Anhydrous ammonia, NH_3, contains 82.3 per cent nitrogen and can usually be purchased at half the price of solid nitrogen fertilizer. It is a gas at normal temperature and pressure but can be shipped as a liquid under increased pressure. After application to a depth of 4 to 6 inches by means of a knifelike device, the ammonium ion is adsorbed by the soil exchange material. It may then be taken up by the plant or converted to nitrate by soil organisms.

Because of great danger of stock injury, anhydrous ammonia can be used in forest nurseries only for preparation of sawdust composts or for application on fallowed soils treated with peat or other raw organic remains (Voigt *et al.,* 1950). The use of liquid ammonia for the preparation of peat composts must be made with great caution. A high concentration of ammonia gas breaks down fibrous peat into a highly dispersed mucklike material of unsatisfactory physical properties.

Organic nitrogen fertilizers. This group of fertilizers includes dried blood, tankage, steamed bone-meal, horn shavings and meal, dried ground fish, cottonseed meal, activated sewage sludge, garbage tankage, tobacco stems, linseed meal, and soybean meal. These fertilizers carry between 2 and 15 per cent nitrogen and varying amounts of phosphorus and other nutrients, including trace elements. Although these fertilizers are widely used in nursery practice, none of them is entirely satisfactory. The chief objections are the high price, encouragement of parasitic organisms, and danger of chemical injury of seedlings. The chemical injury occurs at a high temperature and an abundant supply of water, conditions which stimulate a rapid release of ammonia.

PHOSPHATE FERTILIZERS

Rock phosphate, $3Ca_3(PO_4)_2 \cdot CaF_2$, occurs as phosphorite rocks. It is about 70 per cent tricalcium phosphate and contains about 33 per cent P_2O_5. This is soluble only in strong mineral acids and is not directly available to the seedlings. In time, however, the water and carbon dioxide of the soil may convert the tricalcium phosphate into available monocalcium phosphate.

$$Ca_3(PO_4)_2 + 4CO_2 + 4H_2O \rightarrow CaH_4(PO_4)_2 + 2Ca(HCO_3)_2$$

Because this process is slow, rock phosphates are used for the permanent improvement of soils rather than for an immediate supply of available phosphorus. In some cases, rock phosphate may be advantageously added to the compost made of acid peat. Also, the rock phosphate may be used when strongly acid peat is applied in large quantities on nursery soils, as well as when the soil is treated with sulfur. Inoculation of soil with sulfur-oxidizing bacteria or an addition of leaf mold may speed up considerably the release of available phosphorus. Some rock phosphates are toxic to forest seedlings because of their high content of fluorine.

Superphosphate, $Ca(H_2PO_4)_2$, is essentially monocalcium phosphate and is manufactured by treating rock phosphates with sulfuric acid, as follows:

$$Ca_3(PO_4)_2 + 2H_2SO_4 + 4H_2O = CaH_4(PO_4)_2 + 2CaSO_4{\cdot}2H_2O$$

Commercial superphosphate usually contains 20 per cent available phosphoric acid (P_2O_5), partly in the form of monocalcium and partly in the form of dicalcium phosphate. It is the phosphate fertilizer which is most commonly used in forest nurseries for preparation of composts and in broadcast applications. In addition to phosphorus, low-grade phosphates carry appreciable amounts of both calcium and sulfur, and, therefore, are particularly suited for soils that have a shortage of these two elements. For such soils, application of superphosphate may reach 600 pounds per acre. The superphosphate is not easily soluble in water and cannot be used for liquid treatments of nursery stock or for top dressings of soils supporting forest plantations.

In strongly acid soils the superphosphate may be converted into ferric phosphate or aluminum phosphate which are not readily available to plants. This process of "phosphate fixation" may be prevented by the addition of lime, wood ashes, or organic remains. On the other hand, in slightly acid or alkaline soils the superphosphate may be converted to the less available hydroxy apatite. This may be prevented by the addition of ammonium sulfate and other acid-forming materials.

Double superphosphate, or treble superphosphate, known also under the trade name "Multiphos," carries 40 to 50 per cent available phosphoric acid (P_2O_5). It is prepared by treating phosphate rock with phosphoric acid instead of with sulfuric acid:

$$Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$$

Double superphosphate is particularly suitable for use on nursery soils well-supplied with calcium and on soils which need large quantities of phosphorus. In a single application, as much as 300 pounds of this fertilizer may be applied per acre if it is thoroughly worked into the soil.

Metaphos or **calcium metaphosphate,** $Ca_3(PO_3)_6$, is produced by the TVA. Assaying 65 per cent phosphoric acid, it is an excellent source of phosphorus when used in acid soils.

POTASSIUM FERTILIZERS

Muriate of potash, or **potassium chloride,** KCl, is manufactured by purifying natural potash deposits. It contains nearly 50 per cent potash (K_2O), is soluble in water, and is for the most part readily available to seedlings. In the soil it splits into potassium and chlorine ions. The former are absorbed by the colloidal fraction of the soil and utilized by the plants, probably in the form of carbonates; the latter form hydrochloric acid:

$$KCl + H \cdot x \rightarrow K \cdot x + HCl$$

$$2K \cdot x + H_2CO \rightarrow K_2CO_3 + 2H \cdot x$$

Some of the liberated hydrochloric acid is employed in converting calcium phosphates into available form, and some is leached. In large quantities the chlorine ion is toxic to forest seedlings (Němec, 1932), and where large amounts of potash are needed, potassium sulfate should be used instead of muriate of potash. Because potassium salts are easily washed from the soil in the absence of base exchange material, the need for large and repeated applications of potash fertilizer is to be expected on sandy soils poor in clay and organic matter (Wilde and Kopitke, 1940). The rate of application of muriate of potash varies ordinarily from 100 to 300 pounds per acre at a time. In purchasing potash fertilizers one should be sure that the salt does not contain borax, which is injurious to plants except in minute amounts.

Sulfate of potash, K_2SO_4, is made by treating muriate of potash with sulfuric acid or magnesium sulfate. About 50 per cent of it is potash (K_2O). It may be used in somewhat larger quantities than muriate of potash without injury to the roots of the seedlings. In other respects it is similar to muriate of potash.

Potassium-magnesium sulfate, sold under the name of "Sul-Po-Mag," is a double salt of potash magnesia, $K_2SO_4 \cdot 2MgSO_4$. It contains 11 per cent elemental magnesium and about 19 per cent potassium. This fertilizer can be advantageously used for correction of potassium and magnesium deficiencies in soils of both nurseries and forest plantations.

Crude potash salts, kainite, sylvinite, and carnallite, contain from 9 to 16 per cent potassium chloride and have some sodium chloride and magnesium sulfate. The chemical composition varies greatly according to the mine. Materials from some deposits may be toxic to seedlings. Total destruction of the nursery stock has been reported as the result of the application of large amounts of crude potash fertilizers. The toxicity of these fertilizers is directly related to their content of chlorides, especially those of sodium.

Several studies indicated that finely ground potassium feldspar is available to coniferous seedlings and may be of particular value in treatment of poorly buffered sandy soils (Rosendahl, 1943).

Wood Ashes contain from 2 per cent to 8 per cent K_2O, some P_2O_5, and a large amount of CaO. Because of the presence of trace elements, wood ashes appear to be superior to other sources of potash, but they are seldom procurable in quantity. They should be used with caution if the area is to be seeded to conifers predisposed to damping-off disease.

COMBINED FERTILIZERS

This group includes fertilizers containing two or three essential nutrients. Most of the combined fertilizers find their greatest use in forest nursery practice in liquid treatments.

Monoammonium phosphate, $NH_4H_2PO_4$, is made by treating phosphoric acid with ammonia and evaporating the solution. It contains about 11 per cent nitrogen and 48 per cent phosphoric acid. It is sold under the trade name "Ammo-Phos."

Diammonium phosphate, $(NH_4)_2HPO_4$, is essentially a mixture of monoammonium phosphate with ammonium sulfate in the proportion of about 800 pounds of crude ammonium phosphate to 1200 pounds of ammonium sulfate. The commercial product, called "Diammono-Phos," has about 16 per cent nitrogen and 20 per cent phosphoric acid.

Nitrophoska is a trade name for a group of highly concentrated synthetic fertilizers manufactured in Germany. These are made by bringing into contact solutions of diammonium phosphate, ammonium nitrate, and potash salts and then precipitating out the resulting salt. The four commonly used grades of Nitrophoska are: No. 1, N—15 per cent, P_2O_5—30 per cent, K_2O—15 per cent; No. 2, N—16.5 per cent, P_2O_5—16.5 per cent, K_2O—21.5 per cent; No. 3, N—15.5 per cent, P_2O_5—16.5 per cent, K_2O—19 per cent; No. 4, N—15 per cent, P_2O_5—11 per cent, K_2O—26.5 per cent.

Potassium nitrate, KNO_3, occurs in natural deposits and is manufactured from nitrate of soda and muriate of potash. It is about 13 per cent nitrogen and 45 per cent potash. This salt frequently fills exactly the needs of nursery practice.

Potassium ammonium-nitrate is manufactured in Germany and is known also under the trade name "Kali-Ammon-Salpeter." It carries about 27 per cent potash and 16 per cent nitrogen, half of which is in the nitrate form and half in the form of ammonia. This fertilizer is made with the object of reducing the hygroscopic properties of ammonium nitrate. It is well adapted for use in forest nurseries.

Potassium metaphosphate, $K_6(PO_3)_6 \cdot H_2O$, a TVA product which is a good source of two fertilizer elements, phosphorus and potassium. Of importance is the fact that plant nutrients constitute 90 per cent of this fertilizer (55 per cent P_2O_5 and 35 per cent K_2O). It is not as yet in commercial production, but when manufacturing costs are reduced it should find wide usage.

Bone phosphate contains about 50 per cent tricalcium phosphate and about 4 per cent nitrogen. Bone phosphate is a favorite source of phosphorus in greenhouse and commercial nurseries, chiefly because it provides some extra nitrogen and because it produces no toxic effect upon the plants when applied in large quantities. However, it is an expensive fertilizer which cannot compete in forest nursery practice with the other forms of phosphate.

Mixed fertilizers are composed of different mixtures of salts, such as ammonium sulfate, superphosphate, and potassium chloride or potassium sulfate. The composition of these fertilizers is given by their grade or analysis—the percentage of nitrogen, phosphoric acid, and potash stated in whole numbers. For example, 3–9–18 means 3 per cent N, 9 per cent P_2O_5, and 18 per cent K_2O. These figures total only 30 per cent, or 30 pounds per 100-pound bag. The remaining 70 pounds are made up by sulfates, chlorides, and other ions. Also, a small amount of the filler, such as dolomite or sand, may be included. The common fertilizer mixtures suitable for use in forest nurseries are: 3–9–18, 6–6–18, and 0–9–27.

Es-min-el, or "essential minor elements," is a trade name of a fertilizer containing different amounts of manganese, copper, zinc, and boron and traces of other minor elements. It may be used for soils of old nurseries whose supply of trace elements is approaching a critical level. Because of the high toxicity of trace elements, special precautions must be taken in applying this fertilizer.

LIME

The term "lime" is used to designate a number of compounds, including the oxides, hydroxides, or carbonates of calcium and magnesium, such as burned lime or quicklime, air-slaked lime, water-slaked or hydrated lime, waste lime or by-product lime, marl, ground shell lime, and ground limestone. With few exceptions forest nurseries use only ground limestone, obtained by grinding calcitic or dolomitic rock. It is agreed that 75 per cent or more of the ground material should pass a 100-mesh sieve and should contain calcium and magnesium carbonate equivalent to not less than 45 per cent of calcium oxide. Use of burned or slaked lime is dangerous because it may lead to the injury or "burning" of roots.

The rate of application of ground limestone on forest nursery soils may be as high as 5 tons per acre. Such a high application may be necessary on soils of rather heavy texture and a reaction of about pH 4.0. On less acid and sandy soils the amount of lime is decreased proportionately. The general tendency in lime application on nursery soils should be to apply just enough lime to bring the soil reaction to pH 5.0 when growing conifers and to pH 6.0 when growing hardwoods.

It is highly desirable that the application of lime, whatever the form and whatever the rate, be made well in advance of seeding, for addition of lime may promote a severe outburst of damping-off disease. Ordinarily, applications of lime are made ahead of green manure crops, and the treated area then is devoted to transplants which remain in beds for one or two years. During this period, the harmful effects of the lime are alleviated.

Additional information on the use of commercial fertilizers and lime is given in comprehensive volumes by Lyon *et al.* (1952) and Collings (1955).

COMPOSTED FERTILIZERS

Types of composted fertilizers. Composts are usually prepared by compounding various organic and mineral materials, such as peat, forest litter, animal manure, lime, wood ashes, and commercial fertilizer salts. A mixture of these materials is watered or exposed to rainfall and allowed to remain until fermentation or physico-chemical reactions produce a more or less homogeneous fertilizer. The knowledge of compost preparation is ancient and probably stemmed from China (King, 1926). The practice has been in common use in Europe for at least 400 years; "And do not spread the compost on weeds to make them ranker . . ," states one of Shakespeare's characters.

In spite of its respectable age, the expression "composting" is often unjustifiably used as a synonym for decomposition or fermentation. Actually, the word compost is defined in the dictionary as "composite, mixture, or compound," and may or may not imply fermentation. Depending on the nature of organic remains, composted fertilizers fall into three groups:

> **Fermented composts,** prepared from organic remains which undergo rapid and nearly complete decomposition and which retain nutrients largely in tissues of microorganisms.
>
> **Inert composts,** prepared from decay-resistant organic matter, chiefly peat, which acts exclusively as a sponge and exchange material adsorbing soluble nutrients.
>
> **Partly activated composts,** made from a mixture of decomposable and decay-resistant organic remains which retain released or added mineral salts partly by biological fixation and partly by physico-chemical adsorption.

Fermented composts are prepared from straw, green manure crops, forest litter, raw humus, and sawdust. Composts of this type are excellent fertilizers, but they are costly and many of them undergo rapid decomposition in nursery soils.

Inert composts, made from decay-resistant peat, persist in the soil for a long time and are the least expensive, but they tend to produce a shortage of nitrogen. Such composts require periodic analyses and supplementary treatments with soluble nitrogen fertilizers.

Partly activated composts usually best fill the average requirements of nursery practice.

For a long time compost was looked upon only as a source of plant nutrients, and with the development of the fertilizer industry the importance of compost temporarily decreased. Within the past two or three decades, however, studies of the biological and base exchange properties of soils have placed an entirely new emphasis upon the importance of composted fertilizers. It became evident that the chief benefit of compost lies not in the nutrients released from plant remains, but in either the biochemical or the adsorbing effects of the organic matter. Considering the availability of materials, the preparation of composts in nursery practice is largely limited to two major types: partly activated peat composts prepared from peat, forest litter or raw humus, and commercial fertilizers; and fermented compost prepared from sawdust treated with anhydrous ammonia and phosphoric acid and inoculated with cellulose-decomposing fungi.

Preparation of peat composts. A selection of suitable peat material requires a thorough examination of the morphological features of the peat deposit to the depth of excavation and the determination of the following chemical properties: reaction, exchange capacity, total nitrogen, and carbon-nitrogen ratio. Fibrous peat derived from mosses and sedges has the most desirable physical makeup for preparation of composts and soil improvement. The use of colloidal or macerated peat should be avoided, since such materials tend to cement soil into a concrete-like crust. Strongly acid peat with a reaction of pH 5.5 or lower is best for forest nurseries, particularly those raising coniferous stock. Peat of a reaction of pH 5.5 to 7.0 may be satisfactory for hardwood or transplant beds, but it is seldom desirable for soils supporting coniferous seedlings because of the danger of damping-off and root-rot diseases. The use of alkaline peat is questionable because of the danger of diseases and toxicity of carbonates. Peat of high quality should analyze at least 1 per cent total nitrogen and possess a minimum exchange capacity of 70 m.e. per 100 g. Peats with a wide carbon-nitrogen ratio require high applications of soluble nitrogen, but otherwise they may be valuable because of their high exchange capacity and stability in soils.

The peat is dug by hand, by means of a dragline, or by power shovel. The digging should be done in the driest period of the year. The material is left to dry out at the place of excavation so that a minimum amount of water will be transported. The peat is transported to the nursery and forced through a shredding machine which is usually attached to the drive shaft or rear wheel of an old automobile.

If forest litter or raw humus is used in the preparation of the compost, it should be collected from older, preferably mixed hardwood-coniferous stands which show appreciable accumulation of raw organic remains. Because removal of the litter is detrimental to forest stands, it should be confined to scattered small areas, especially to depressions where litter accumulates in excessive quantity. Areas invaded by parasitic organisms must be avoided. Litter of alkaline reaction may prove to be unsatisfactory.

Composts are stratified in a heap, in any natural depression, or in special pits made of wood or concrete. In large nurseries pits are usually built entirely of concrete except for removable wooden gates

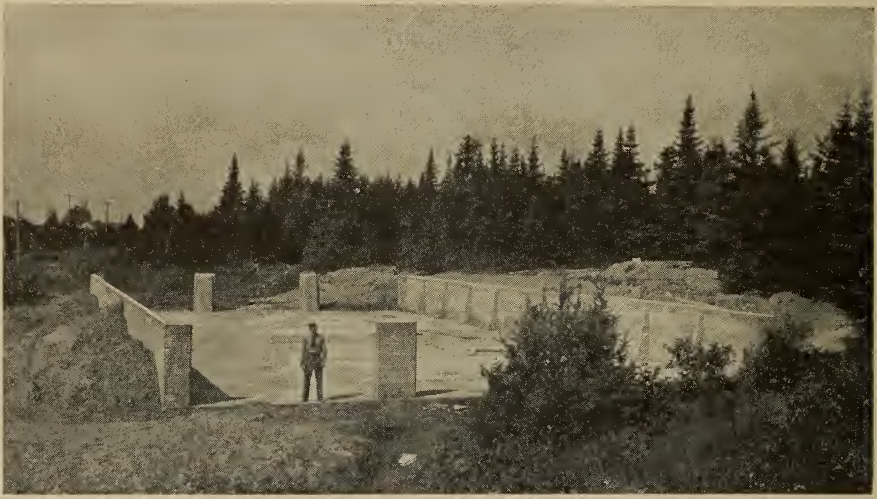


Fig. 11–3. Construction of a concrete compost pit for a nursery about 40 acres in size. Northern Michigan. (Manistique Nursery, U. S. Forest Service.)

(Fig. 11–3). If possible, the pit should be cut into a slope of considerable angle so that gravity will assist in both loading and unloading the pit.

In the preparation of small quantities of peat compost, a one-inch layer of shredded peat is placed on the bottom of the compost pit or pile. On top of this is broadcast a mixture of commercial fertilizers. The fertilizers are covered with a thin layer of litter which may be followed by a layer of soil. The materials are thoroughly sprinkled with water. On top of the litter or soil is piled another one-inch layer of peat, followed by the fertilizers and litter as previously described. This is repeated until the pit is filled.

The amount of fertilizers to be applied to separate layers of the compost is calculated from the total amount of fertilizers used per acre and the amount of compost applied per 100 square feet of seedbed. Suppose that a nursery soil needs 250 pounds of ammonium sulfate, 200 pounds of superphosphate, and 150 pounds of muriate of potash per acre, and that the intention is to apply 1 cubic foot of compost per 100 square feet of seedbed. Since 1 acre is about 40,000 square feet, the total amount of compost needed per acre is 400 cubic feet. Consequently, the entire amount of commercial fertilizer needed per acre should be distributed in 400 cubic feet of composted material. If the compost pit is 48 feet long and 20 feet wide, a one-inch layer will hold 80 cubic feet of compost ($48 \times 20 \times 1/12$). Thus, a five-inch layer of material will be sufficient to fertilize an acre of seedbeds. This means that one-fifth of the total acre application of fertilizer must be broadcast over a one-inch layer of organic matter. The application, then, would be 50 pounds of ammonium sulfate, 40 pounds of superphosphate, and 30 pounds of muriate of potash.

For a more exact calculation of the amount of each fertilizer (f) to be broadcast over a one-inch layer of organic material, the following formula may be applied:

$$f = \frac{F \times L \times W}{12 \times 435 \times C}$$

where F is the amount of any one fertilizer to be applied per acre, L is the length of the pit, W is the width of the pit, and C is the amount in cubic feet of compost to be applied per 100 square feet of seedbed.

According to this formula the amount of ammonium sulfate to be applied in the given case would be:

$$f = \frac{250 \times 48 \times 20}{12 \times 435 \times 1} = 46 \text{ pounds}$$

Instead of stratifying the materials, some nursery men feed a shredding machine by means of a conveyor, supplying peat, litter, mineral fertilizers, and soil in the desired proportions. The proper amounts of peat, litter, and commercial fertilizers are applied to the conveyor by means of shovels and scoop cups of known volume. It appears that the materials are mixed more effectively in this way than in stratification. For maximum efficiency the shredding machine should be placed on the very edge or rim of the pit, so that the shredded material is discharged directly into the cavity.

In small nurseries and in nurseries with fertile soils an application of compost may correct the deficiencies both of mineral nutrients and of organic matter. In large nurseries it is more economical to correct deficiency of organic matter by direct application of peat. This makes it possible to reduce the quantity of peat used in composting to the very minimum necessary as a carrier of fertilizers. Such practice leads to the use of highly concentrated composted fertilizers carrying as much as 60 pounds of mineral salts per cubic yard of organic matter.

Although concentrated compost offers a financial saving, it may cause chemical injury to the roots of seedlings. For this reason the utmost care should be taken to incorporate the concentrated compost fertilizer into the soil to a minimum depth of 7 inches. Before application, concentrated compost may be mixed with raw peat in proportions of 1:1, 1:2, or 1:3, depending upon the deficiency of soil organic matter. This mixing or "diluting" of compost with peat is usually done by forcing both materials through the shredding machine in the desirable proportions.

Investigation of the effect of salt concentration in nursery composts upon microorganisms and higher plants (Krumm, 1941) indicated that 50 to 60 pounds of total fertilizer salts per cubic yard of composted organic matter is an average desirable concentration. Composts carrying less than 25 pounds of salts per cubic yard were found uneconomical. Composts with concentrations of salts exceeding 80 pounds per cubic yard suffer considerable losses of certain nutrients by leaching, may become unbalanced, and present danger of chemical injury to nursery stock (Fig. 11–4).

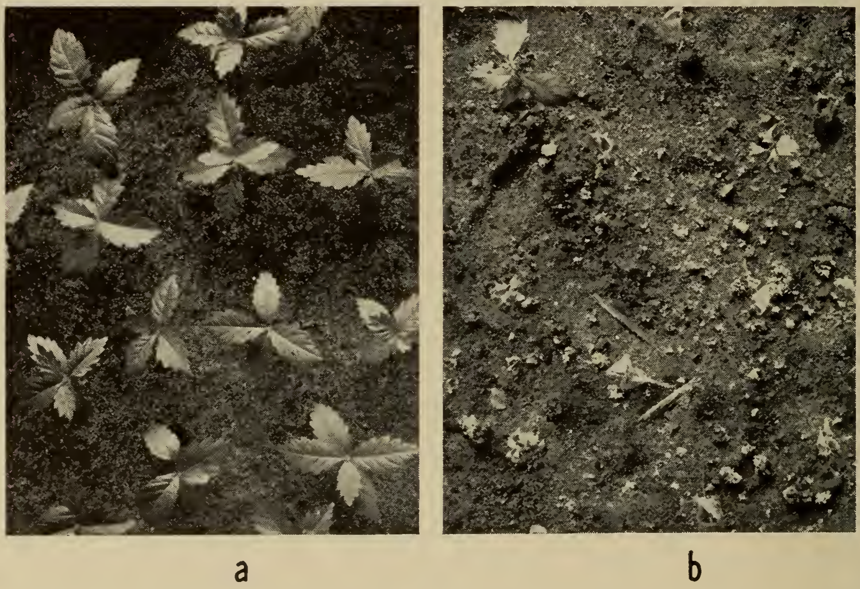


Fig. 11–4. Effect of composted fertilizers on the growth of elm seedlings: (*a*) nursery soil treated with compost of a reasonably low concentration of fertilizer salts; (*b*) similar soil treated with compost carrying a high concentration of soluble salts. (After C. J. Krumm, 1941.)

In order to facilitate the incorporation of salts with organic matter the compost should be kept moist and reworked at least once, but better several times, during the year. This is facilitated by the use of motorized equipment. Prolonged excessive wetness may cause unfavorable biological and chemical changes in the composition of the compost.

According to general belief, the compost attains its best quality when it becomes a uniform mass, in which the separate constituents can no longer be recognized. Such decomposition is of rare occurrence in silvicultural practice dealing with acid and resistant types of peat, and the degree of compost decomposition plays only a minor part in soils of forest nurseries. It is extremely important, however, that the compost have a sufficient amount of available nitrogen. This must be determined by periodic analyses and any deficiency corrected by the addition of soluble nitrogen fertilizers.

It cannot be stated too strongly that the quality of a composted fertilizer depends on its content of forest litter, whose beneficial effects have been known for ages. It is with good justification that Ibsen's Peer Gynt states, "Withered leaves, not in vain were you begotten, you'll as compost serve when rotten." Forest litter in all its morphological modifications serves as the principal seat of microbiological activity and the source of both available nutrients and hormone-like growth-promoting substances. The value of the addition of litter is striking illustrated by Fig. 11–5.

Preparation of sawdust compost. Depending on conditions, sawdust composts may be prepared either at the sawmill or directly on nursery blocks. The first method is applicable to continuous large-

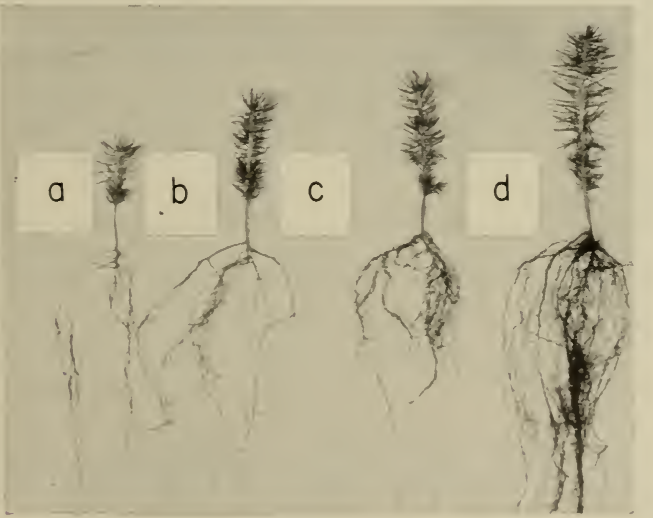


FIG. 11–5. Growth of 2-year-old white spruce seedlings under different fertilizer treatments: (*a*) check; (*b*) twenty tons of raw peat, 1500 pounds rock phosphate, and 3000 pounds ground feldspar per acre; (*c*) same as *b* plus 700 pounds of soluble NPK fertilizer per acre; (*d*) same as *c* plus 5 tons of hardwood-hemlock litter per acre. (After Wilde, 1946.)

scale production, whereas the latter is suitable for improvement of a single nursery.

A reasonably level, stone-free soil, preferably of sandy texture, located near the sawmill is an essential prerequisite for manufacturing sawdust compost on a large scale. The sawdust pile is leveled to a rectangle of uniform 4-foot depth. The material is first treated with anhydrous ammonia, supplied from a 500-gallon tank. The outlet valve of the tank is connected to an Ammotrol Regulator, type A (Weatherhead Co., Cleveland, Ohio). The regulator, in turn, is connected with a hollow aluminum probe by means of a 50-foot heavy rubber hose. The probe, 4 feet long and $\frac{11}{16}$ inches in outside diameter, is closed on the end and perforated spirally by $\frac{1}{64}$-inch holes at $\frac{1}{2}$-inch spacing. The ammonia is applied by jabbing the probe vertically into the pile at 2-foot intervals. With this spacing, each jab of the probe treats 16 cubic feet of sawdust. The anhydrous ammonia is applied at the rate of 9 to 12 pounds per cubic yard of sawdust. The pile is left undisturbed for about ten days and then treated with a 4 per cent solution of phosphoric acid, applied at the rate of 8 gallons per cubic yard of sawdust. This serves to adjust the pH of the material to 6.5. Enough potassium sulfate is added to the phosphoric acid solution to satisfy the requirement of 2.5 pounds of K_2O per cubic yard of sawdust. To facilitate operation the sawdust is spread on a 4- to 6-inch layer and the solution is applied by means of a multi-sprayer or a motor-driven pump. A 24-hour period is allowed for complete absorption of the solution before the sawdust is inoculated with *Coprinus ephemerus,* the cellulose-decomposing organism. This inoculum consists of approximately 1 per cent by volume of material previously composted by this process (Davey, 1953, 1955).

If the fermentation is allowed to proceed in the pile, the sawdust must first be stratified with soil which furnishes organisms to carry the process past the stage reached by the *Coprinus.* However, it has been found that fermentation is more efficient when, after the addition of inoculum, the sawdust is rototilled into the soil. In all probability, the soil provides better physical conditions than does the compost pile.

The composting material should be kept generously watered. Depending on the temperature and nature of the sawdust, 8 to 14 weeks are required to complete the fermentation, after which the compost may be applied to nursery beds. In removing the compost, it is desirable to leave a thin layer of material on the ground. This residue can serve as inoculum for the preparation of the next compost.

Sawdust compost may also be fermented in the soil of the particular nursery block requiring treatment. In this procedure a strip of fresh, moist sawdust is placed along the border of the block in a 6-inch layer. Anhydrous ammonia, at a rate of 9 to 12 pounds per cubic yard of sawdust, is injected by means of the knife-like device employed for regular soil treatments with this fertilizer. The blades should be set to deliver the ammonia at a depth of at least 6 inches; if a more shallow application is made there is danger of a considerable loss of ammonia by volatilization. After 10 days the sawdust is treated with the solution of phosphoric acid and potassium sulfate; 24 hours later inoculum of *C. ephemerus* is sown over the material by means of a manure spreader. Then the sawdust is spread over the entire area and is rototilled into the soil.

It is most practical to use this method of sawdust composting in the fall, so that the following spring the block can be used for seed or transplant beds. If the compost is prepared early in the spring, the area should be sown to a green manure crop, which is plowed under the next fall.

To initiate preparation of sawdust compost, it is first necessary to prepare a sufficient quantity of inoculum carrying *Coprinus ephemerus*. To accomplish this it is sufficient to ferment sawdust in a few 50-gallon barrels placed in a shed or other structure where ammonia fumes will not be objectionable. The barrels are filled with fresh sawdust, preferably that of hard maple, and treated with anhydrous ammonia at the rate of 3 pounds per 50-gallon barrel. For this purpose anhydrous ammonia is procured in a small cylinder. The treated sawdust is left undisturbed for one week, removed from the barrel, spread on the floor, and neutralized with a solution of phosphoric acid enriched in potassium sulfate. The material is thoroughly reworked with a shovel and left on the ground for a few days; then about a gallon of inoculum, previously prepared or secured from an institution using this method of composting, is spread over 50 gallons of material. The sawdust is thoroughly mixed, and replaced in the barrels for composting. The material is kept moist by periodic watering and is frequently aerated. The aeration can be accomplished by the aluminum probe attached to an air compressor. Otherwise the compost can be occasionally remixed. If the composting medium is prepared satisfactorily, within a few weeks the appearance of fruiting bodies of *Coprinus ephemerus* will indicate the success of the inoculation (Fig. 11–6). Simultaneously, all of the sawdust becomes permeated with white fungal hyphae and attains a temperature of above 100° F. At this stage the medium is suitable for inoculation of other chemically treated sawdust. Ordinarily, it is

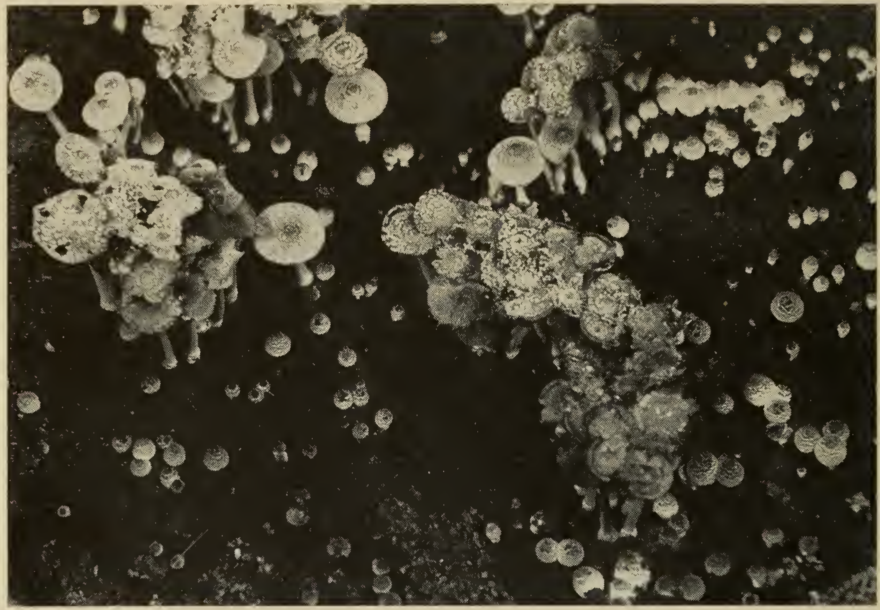


Fig. 11-6. Abundant crop of fruiting bodies of *Coprinus ephemerus* reveals the success of inoculation of chemically treated sawdust.

sufficient to use 1 per cent of inoculum for the preparation of a large quantity of sawdust compost.

Rate and manner of compost application. The minimum convenient application of composted fertilizer is about 1 bushel per 100 square feet. Under exceptional conditions, however, as little as ½ bushel may be applied per 100 square feet if the compost is thoroughly mixed with raw organic matter.

The amount of applied compost varies with the level of soil fertility and nutrient requirements of nursery stock. The standard rate of application is established for the prevailing conditions of the nursery soil and for species of average requirements. For instance, in a nursery raising jack pine, red pine, and white spruce, the average rate of application may be 1 bushel per 100 square feet. For jack pine it may be necessary to apply only ½ bushel of compost, while for white spruce it may be necessary to apply 2 bushels. The soil conditions may also essentially modify the standard rate of application, and on poorer blocks of the nursery even jack pine may require an application of 1 or 2 bushels per 100 square feet.

The compost contains nutrients in a fixed ratio which is established to meet the predominant requirements of the soil. This ratio, however, may not be entirely satisfactory for sections of the nursery which have an unbalanced ratio of nutrients. Under such conditions it is necessary to approach the desirable ratio by application of compost and to correct the remaining nutrient deficiencies by the later application of liquid fertilizers. The requirements of different species may also call for additional corrections in the ratio of nutrients pro-

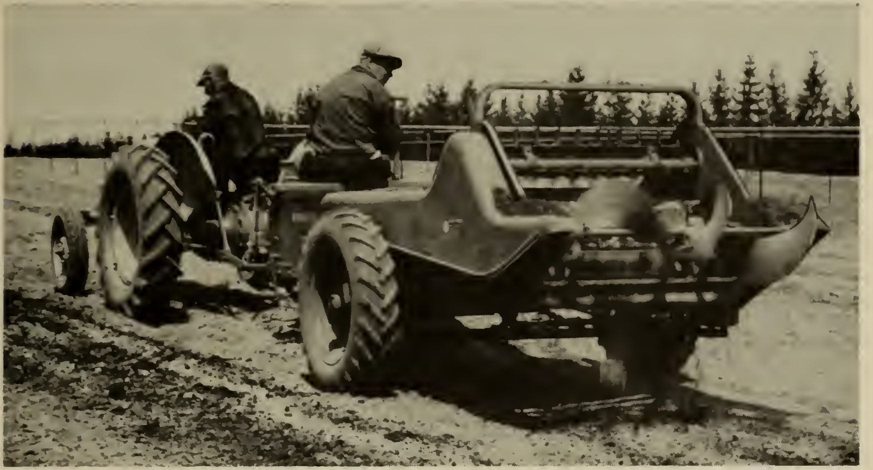


FIG. 11–7. Application of composted fertilizer by a manure spreader. (Wisconsin Conservation Department.)

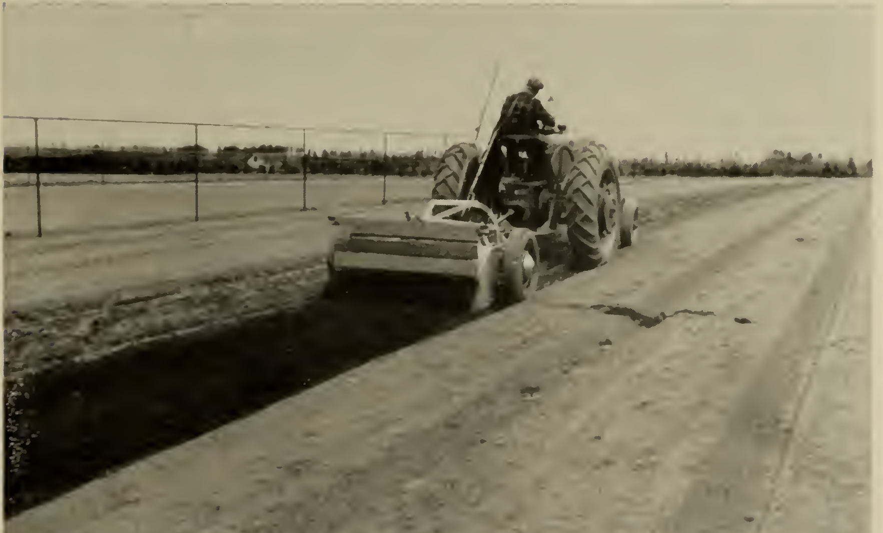


FIG. 11–8. Incorporation of compost by means of a rototiller. (Wisconsin Conservation Department.)

vided by compost. In the majority of cases available nitrogen is the factor which needs additional correction.

The compost is applied either by hand or by means of a manure spreader (Fig. 11–7) and is incorporated into the soil with a rototiller set to approximately a 9-inch depth (Fig. 11–8). If a rototiller is not available, the deep incorporation of the compost can be achieved by double plowing and disking. First the land is plowed to a depth of about 9 inches. This exposes sterile subsoil. About ⅗ of the total application of compost is broadcast over the area and worked into the soil by a thorough disking to a depth of 4 or 5 inches. The fertilized layer is turned under by a second plowing. The remaining compost is then broadcast, disked, and harrowed.

Erratic distribution of the composted fertilizer in the soil may cause injury to the roots through a local excess of soluble salts, and it also produces stock lacking uniformity. A shallow application of compost, aside from the danger of burning, leads to the production of seedlings with superficial root systems (Wahlenberg, 1929). This, in turn, decreases the drought resistance of the produced stock (Fig. 11–9).

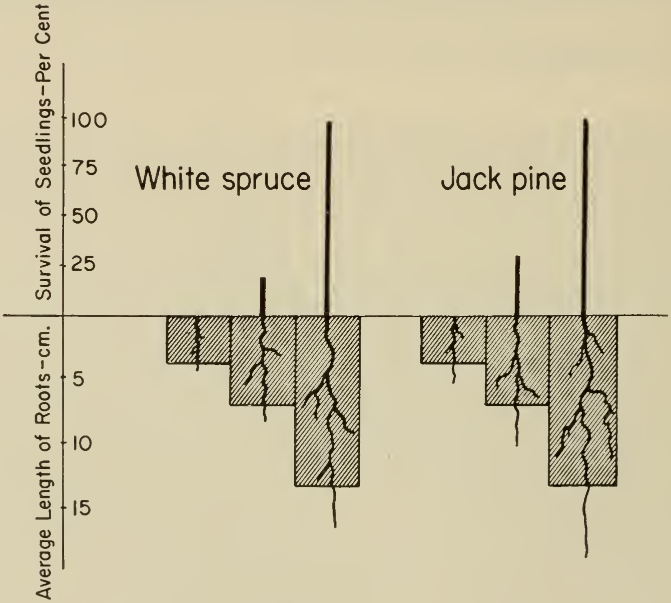


Fig. 11–9. Effect of the depth of application of compost on the length of roots and the resistance to drought of year-old seedlings. Equally watered seedlings in 2-gallon containers were exposed to increasing temperature for 6 hours. The temperature recorded at the end of this period was 125°F. Shaded area indicates the depth of compost application.

LIQUID FERTILIZERS

Need for liquid fertilizers. Ordinarily, fertilizers are applied broadcast prior to seeding or transplanting. These fertilizers should provide enough nutrients for the entire two- or three-year period of stock growth. If for some reason application of fertilizers was omitted, the treatment of nursery stock with fertilizer in solution may become urgent. In some cases even fertilized soils may develop nutrient deficiencies and require an application of liquid fertilizers during the first or second year following seeding or transplanting. The deficiencies may result from heavy rains, unexpectedly high germination of seed, and losses of nutrients through biologic or chemical fixation.

Choice of fertilizers for liquid treatments. Because of the high availability as well as toxicity of salts in solution, particular care should be exercised in the selection of fertilizers for use in liquid treatments.

A deficiency of nitrogen may be corrected by the application of sodium nitrate, ammonium sulfate, ammonium nitrate, double ammonium sulfate-nitrate, urea, or combined nitrogen-phosphate and nitrogen-potassium fertilizers. The choice of either ammonium or nitrate fertilizer depends upon the reaction and biological activity of the soil, as well as upon the species grown. Under average conditions it is advisable to supply about one-third of the nitrogen in the form of nitrates and two-thirds in the form of ammonia. A single application of sodium nitrate and ammonium sulfate in liquid form usually varies from 100 to 250 pounds of salt per acre. Ammonium nitrate is used at the rate of 50 to 150 pounds per acre.

Most of the phosphate fertilizers are not readily soluble in water. However, nursery soils are seldom deficient in phosphorus without being deficient in other essential nutrients, and the deficiency of phosphorus is usually corrected by readily soluble combined fertilizers, such as Ammo-Phos (16–20–0, 11–48–0), or Nitrophoska (15–15–19, 15–11–26). The application rate of combined phosphate fertilizers varies greatly, depending upon the concentration of ingredients, but seldom exceeds 400 pounds of salt per acre.

Potassium in liquid form may be supplied either as potassium sulfate or potassium chloride. The former is preferable because of the lesser toxicity of the sulfate ion as compared to the chloride ion. Potassium nitrate or "Potnit" (13–0–44) and potassium-ammonium nitrate (16–0–27) are more expensive but valuable sources of potash on soils deficient in both available potassium and nitrogen. Muriate or sulfate of potassium are applied at the rate of 100 to 300 pounds per acre at a time. A single application of potassium nitrate may be as heavy as 400 pounds per acre.

In the majority of cases, the fertilizer for liquid treatments is prepared by mixing the individual salts in a proportion to satisfy the requirements of the seedlings on a given soil. The combination of ammonium phosphate, potassium nitrate, and ammonium sulfate or urea gives about the most desirable fertilizer for average nursery soils. The main advantages of this combination are high solubility of all ingredients and an absence of undesirable residues.

Concentration of fertilizer solution and application rate. The amount of total fertilizer salts applied at one time in solution should not exceed 600 pounds per acre, whereas the concentration of applied solution should not exceed 20,000 ppm., or roughly 8 pounds of total fertilizer salts per 50 gallons of water. The following example illustrates the method of mixing the fertilizers in proper amounts.

Suppose the analysis of a strongly acid soil growing coniferous seedlings showed a need for about 40 pounds of available nitrogen, to be provided partly as ammonium and partly as nitrates, 50 pounds of phosphoric acid, and 100 pounds of potash per acre. These amounts of nutrients may be obtained by using 100 pounds of ammonium phosphate (11–48–0) and 200 pounds of potassium nitrate (13–0–44), which combination will give 37 pounds of nitrogen, 48 pounds of phosphoric acid, and 88 pounds of potash per acre, or roughly, per 40,000 square feet. If the fertilizers are to be dissolved in 48 gallons of water and the rate of application is to be 6 gallons per 100 square feet, the following amounts of each salt should be used in the preparation of solution:

$$\text{Ammonium phosphate: } \frac{100 \times 100 \times 48}{40{,}000 \times 6} = 2 \text{ pounds}$$

$$\text{Potassium nitrate: } \frac{200 \times 100 \times 48}{40{,}000 \times 6} = 4 \text{ pounds}$$

As a general rule the application of a balanced liquid fertilizer, including nitrogen, phosphorus, and potassium, gives much better results than the application of single ingredients. Especially in the correction of nitrogen deficiency it is advisable to supplement nitrate or ammonium with a small quantity of both phosphorus and potassium, even on soils having a fairly high content of these two nutrients. The complete solutions prevent possible imbalance in nutrition which may result from the higher availability of dissolved salts as compared with nutrients present in the soil in the form of minerals or replaceable ions.

Distribution of fertilizer solution. In the treatment of smaller areas, 50-gallon barrels are conveniently used for dissolving the salts. The liquid is distributed with 12-quart cans, one can per 4 by 12-foot bed. The amount of liquid in a 50-gallon barrel will thus suffice for the treatment of 800 square feet. The salts are added to the barrel by using measuring scoops cut from tin cans to the proper size, according to the weights of individual fertilizers used.

Because application by hand is slow and costly, small tanks or barrels mounted on wheels were used in some nurseries. However, this type of equipment fails to maintain a constant concentration of applied solution and does not supply the liquid at a sufficiently uniform rate.

In nurseries of considerable size, the problem is satisfactorily solved by the use of a special 200- or 300-gallon sprayer or tank, mounted on a 1½-ton truck and provided with a pressure pump and a rotating agitator (Fig. 11–10). The agitator facilitates the dissolving of chemicals and prevents the formation of a precipitate; the pressure pump assures a uniform discharge of the liquid. The liquid is distributed through two horizontal spraying pipes with ¹⁄₁₆-inch nozzles. One of these pipes is installed in a permanent posi-

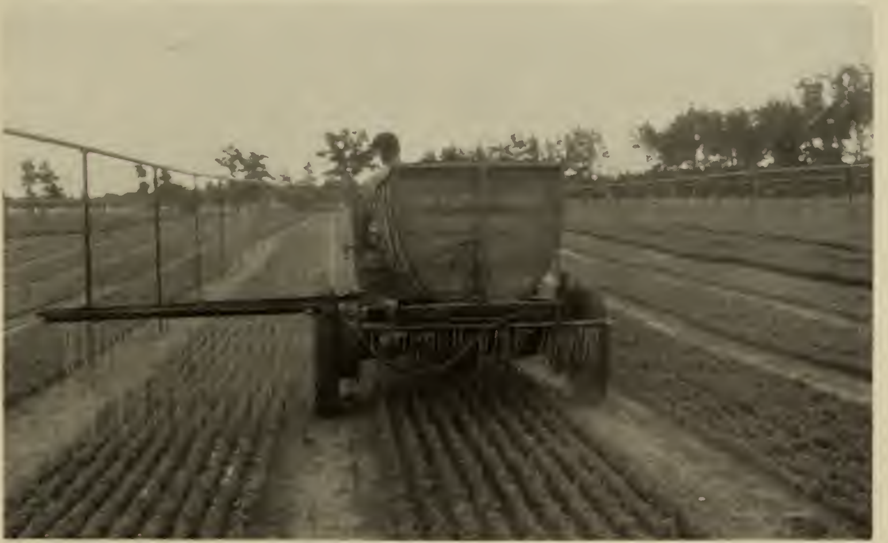


FIG. 11–10. Multiple-use sprayer, provided with a pressure pump and agitators, in the process of applying liquid fertilizer on 2-year-old spruce seedlings. (After W. H. Brener, 1939.)

tion and the other is mounted on a long swinging rod to make it possible to treat beds adjacent to an overhead system line (Brener, 1939).

The sprayer is run in low gear on the paths between seedbeds, and the liquid is sprayed over two rows of seedbeds. The nozzles are arranged in such a position that the spray is delivered chiefly between the rows of seedlings, thus minimizing the danger of "burning" the stock by chemicals and decreasing the amount of watering necessary for dissolving the applied chemicals. The proper distribution of liquid is achieved by regulation of pressure, speed of the truck, and, if necessary, size of the nozzles. Ordinarily, the rate of application is fixed to deliver one gallon per 100 square feet. At this rate it is necessary to make three trips to apply the required 1½ gallons of solution for a 4 by 12 standard seedbed. Therefore, the capacity of the tank suffices to treat over a hundred standard seedbeds, or about 5000 square feet. The relatively slow discharge of the liquid with ¹⁄₁₆-inch nozzles is believed to be desirable, as the repeated spraying covers the area more completely. The efficiency of such a sprayer, considering refilling of the tank, is 400 standard seedbeds per hour, or about 4 acres a day.

In some instances the solution of fertilizers is forced through the overhead irrigation system. In this method, a stock solution is prepared in a large container by dissolving the amount of salts needed for the area to be irrigated. The stock solution is then fed gradually into the system at a sufficiently slow rate to prevent an undesirably high concentration of the applied solution. The chief objection to this method is the difficulty in obtaining a uniform distribution of liquid over the seedbeds. Another disadvantage is that the use of salts may plug or corrode the pipes of the watering system.

Liquid humate fertilizers. "Liquid humate" is a term coined by nurserymen for a suspension of humus obtained by treating forest litter or raw humus with a fertilizer solution. Although this term is not strictly scientific, it is expressive and sufficiently accurate to serve the needs of forestry practice.

Liquid humate includes essential nutrients, growth-promoting substances, and useful microorganisms. When prepared from suitable types of humus it has a remarkably beneficial effect upon the growth of forest seedlings (Fig. 11–11). Of special practical significance is the reviving effect of liquid humates upon stunted, weakened, chemically burned, and even mechanically injured seedlings (Wilde, 1937).

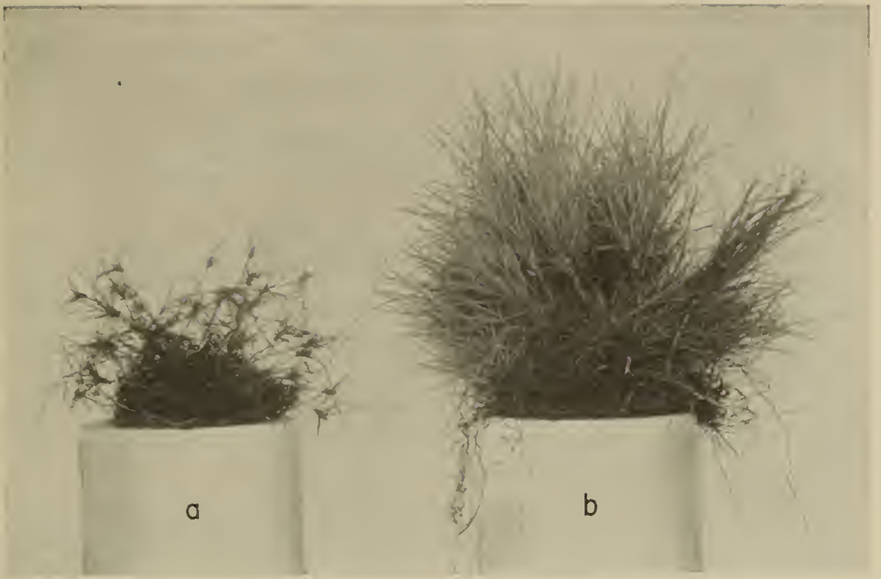


FIG. 11–11. Reviving effect of liquid humate on the growth of 3-year-old red pine seedlings: (*a*) untreated wind-blown sand; (*b*) wind-blown sand treated during the last two years of seedlings' growth with a suspension of hardwood-hemlock litter, ammonium sulfate, ammonium phosphate, and potassium nitrate. (After Wilde, 1937.)

In the preparation of humate for nursery use, enough litter or leaf mold is placed in a barrel or a tank to occupy half the volume of the container. The required amount of mineral fertilizer is added, and the barrel is filled with water from a hose attached to the water system. While the water is being added, the mixture is vigorously stirred. After standing for several hours, the mixture is restirred to bring the fine humus particles into suspension. Then the suspension is siphoned into watering cans and applied to the seedbeds in the manner usually followed in applying liquid fertilizers. When fertilizer is applied on a large area, a battery of twelve or more barrels is employed to speed up the treatment. In order to shorten the carrying distance, the barrels are moved, as necessary, from one block of the nursery to another. The organic residue absorbs a considerable amount of fertilizer and is used as an ingredient of compost or for the direct fertilization of seedbeds.

Preparation of liquid humates requires readily soluble synthetic fertilizers, such as ammonium sulfate, ammonium nitrate, ammonium phosphate, and potassium sulfate. The concentration of salts should not exceed 25,000 ppm., which is equal to about 10 pounds of total salts per 50 gallons of water. The amount of each fertilizer used in the preparation of liquid humate, as well as the rate of application of the suspension, depend upon the content of nutrients present in the soil and the nature of the nursery stock. A formula suitable to an average sandy soil raising pine species may be given as an example: 1½ pounds of 11–48–0 ammonium phosphate, 4 pounds of potassium sulfate, and 3 pounds of ammonium sulfate added to 50 gallons of suspension and applied at a rate of 6 gallons per 100 square feet.

Acid litter from productive hardwood-coniferous stands of tolerant species is most suitable for the preparation of liquid humates. Litter of alkaline reaction and from pioneer stands is least desirable.

The application of liquid humates is expensive and should be limited primarily to stock seriously upset by malnutrition or injured by chemical, climatic, or biotic agents. Liquid humate is the most efficient means of bringing about stock recovery presently available to the nursery manager.

Time of application of liquid fertilizer. In the spring the fertilizers are most efficient and should be applied as soon as the danger of the last killing frost is over. If necessary, the application of liquid fertilizers may be made in two or even three portions, applied at two- or three-week intervals. The last application should be made at least six or seven weeks before the first killing frost, so as to give the seedlings a chance to harden. The application of liquid fertilizer should be made in the early morning, in the evening, or on a cloudy day. The treated beds should be washed thoroughly with water after the application.

As a rule, liquid fertilizers are applied to two-year-old stock. Nutrient deficiencies in one-year-old beds are often difficult to detect from the appearance of the seedlings, and fertilizer application to young stock requires a great deal of caution. Nevertheless, in some instances a light application of liquid fertilizers on 1-0 stock may be more beneficial than heavy applications on 2-0 stock. The seedlings treated during their first year of growth may be allowed considerable time for hardening, whereas the seedlings forced during the second year to meet planting specifications are likely to be succulent and not sufficiently sturdy to withstand the adverse field conditions. If undernourished 2-0 stock is far behind in its development, it is advisable to extend its recovery throughout another growing season, that is, until the seedlings are three years old, or assign such stock to transplant beds. The application of liquid fertilizers to transplants is confined to rare instances.

Timely and appropriate applications of liquid fertilizers must be assured through periodic analyses of soil and careful observations of nursery stock. Frequent analyses are especially urgent in nurseries with poorly buffered sandy soils which are subject to great fluctuations in the level of their fertility.

USE OF GREEN MANURE CROPS IN FOREST NURSERIES

The practice of raising transitional grain or forage crops is used in forest nurseries for a triple purpose: to enrich the soil in organic matter and nutrients, particularly nitrogen; to prevent the leaching of soluble salts; to protect exposed soil from erosion and weeds.

Whenever conditions permit, green-manuring is accomplished with leguminous plants which enrich soil in nitrogen. Various species of lupine, soybeans, and cowpeas are commonly used. Satisfactory results have also been reported with a number of other legumes, particularly vetch, beans, clover, serradella, everlasting pea, and black medic. If high cost of seed or soil acidity do not favor raising legume crops, they may be replaced by less exacting non-legumes. The choice of the latter is largely limited to rye, oats, and buckwheat.

The selection of suitable green manure crops is usually dictated by local conditions, but, in general, preference is given to rapidly growing species having abundant and succulent tops. In most nursery soils the pH value confines the selection of crops to vetch, soybeans, yellow lupine, and non-legumes.

The use of green manures has a strong appeal to nurserymen. This method of soil fertility maintenance does not involve particular difficulties or danger of burning the stock. However, among the many beneficial effects that have been attributed to green-manuring only a few are indisputable under the conditions found in nurseries. Green-manuring improves physical properties of the soil, especially its structure and water-holding capacity. It exerts a conserving influence on the soil nutrients, and, in the case of legume crops, augments the supply of nitrogen (Němec, 1935). The liberation of carbon dioxide and organic acids by decomposing tissues is said to increase the availability of nutrients. On the other hand, the gains in organic matter and base exchange capacity due to green-manuring are too small to satisfy the requirements of most nursery soils. At best, on sandy soils with artificial irrigation green manure crops may help to maintain the level of fertility factors. According to recent findings, green-manuring at times leads to a depletion of the soil in residual humus (Fraser, 1955).

The toxicity of green manure crops to forest seedlings appears to be greatly exaggerated. The high carbon-nitrogen ratio of nonlegume crops is likely to be the condition responsible for inhibited growth of seedlings under unskilled management (Waksman, 1938).

Green manures attain their greatest importance in nursery practice by serving as **catch crops** for commercial fertilizers (Brener and Wilde, 1941). A comparison of available nutrients determined by analysis with growth data and the results of plant tissue analyses has shown that a considerable fraction of applied commercial fertilizers is temporarily fixed by green manure crops as difficultly soluble organic compounds. These compounds, however, become gradually available in the course of plant tissue decomposition and benefit the growth of tree seedlings or transplants (Fig. 11–12). From the standpoint of nursery stock production this conversion of mineral fertilizers into slowly acting and less dangerous organic compounds is just as important as the reduction of fertilizer losses through leaching.

In localities where peat is not available a catch crop is about the safest and most suitable method of fertilization. Under average

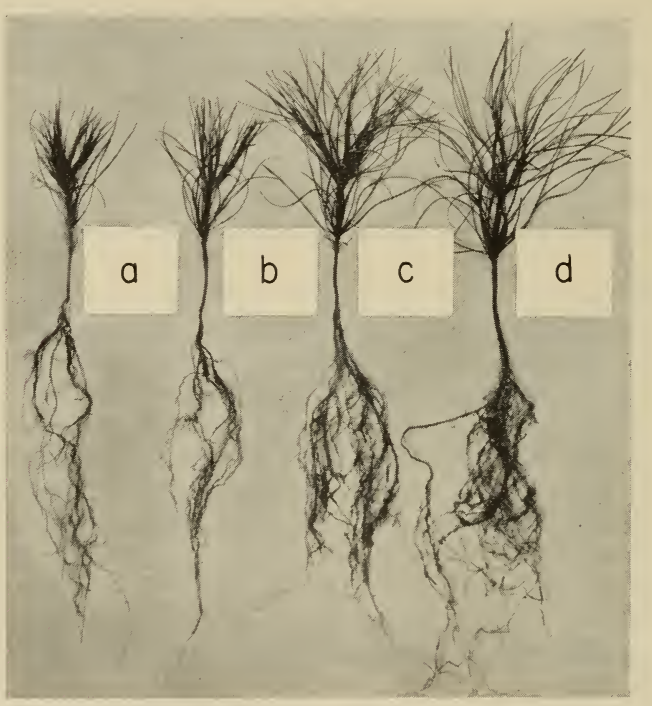


FIG. 11–12. Effect of green manure catch crop on the growth of 2-year-old red pine seedlings: (*a* and *b*) average seedlings raised in sandy soil treated with 1000 pounds of 4-6-10 fertilizer per acre; (*c* and *d*) average seedlings raised in a similar soil treated with the same fertilizer and nonlegume green manure crop. (After Brener and Wilde, 1941.)

conditions, 200 to 300 pounds of superphosphate and 100 to 200 pounds of muriate of potassium per acre may be suggested as suitable applications before seeding legume crops. In raising nonlegumes these fertilizers should be supplemented with 100 to 200 pounds per acre of ammonium sulfate. The state of available nutrients in soil, however, may considerably modify the amount of fertilizers required. The most serious objection to the use of catch crops is the loss of one growing season.

When conditions require a temporary decrease in the production of nursery stock, the area should be kept under a **cover crop** or be used as farming land for raising corn, potatoes, or other agricultural products. Such a practice helps to protect the soil from water and wind erosion, leaching, and infestation with weeds. The beneficial effects of cover crops are unquestionable.

As a general rule, green manure crops are seeded in the spring shortly after the nursery stock is lifted. In the years when a large flight of June beetles is expected, seeding must be delayed until the egg-laying period is over.

The success of green-manuring with legumes depends upon careful inoculation of seed with the proper culture of nodule bacteria (Fred, Baldwin, and McCoy, 1932). Some nursery soils have been inoculated by top dressings of surface soil from a field which previously supported a productive stand of legumes. One hundred pounds of soil is presumably sufficient to inoculate one acre of a nursery. This method, however, is costly and not as reliable as seed inoculation.

Plowing under is done before the crop loses its succulence. Allowing green manure to mature may infest nursery beds with an undesirable volunteer crop; this is especially true in raising buckwheat. The decomposition of the hardened tissues, with their high carbon-nitrogen ratio, may bring about a shortage of available nitrogen.

In plowing under green manures, the furrow slice should not be thrown entirely over, but rather against and onto the adjacent furrow slice. In this way the green manure is distributed evenly throughout the whole layer of surface soil. Deep plowing, however, is recommended in nurseries which do not use artificial methods of damping-off control. At the present time, plowing is often replaced by rototilling which incorporates green manure crops very thoroughly with the soil.

The turned-under green manure is left to decompose until the plant remains do not interfere with the preparation of seedbeds. Tree seed is planted in the fall of the same year or in the following spring. In some instances two crops of green manure are raised during the same growing season, or the green manure crop is followed by a catch crop of non-legumes, usually rye. The second crop is plowed under two or three weeks before the preparation of seed-beds. If the cover crop is left through the winter, at least two weeks should elapse in the spring between the plowing under of green manure and the planting of tree seed or seedlings.

12

> *For, so soon as the first flush of production has passed, the question of how to fertilize most effectively and cheaply demands solution.*
>
> —Hilgard, 1906

Adjustment of nursery soil fertility

Until recently there has been little agreement among the leaders in silviculture on the problems of nursery soil fertility and the use of fertilizers. Even in Germany, the country with the oldest silvicultural practice, the importance of nursery soil fertilization has been fully recognized only during the past few years. A quotation from Dengler's (1930) text on silviculture may help to visualize the confusion which existed in German nursery practice: "The earlier, often expressed idea that the planting stock for poorer sites should not be encouraged by fertilization went so far that the commercial nurseries were offering stunted seedlings as being especially well suited for reforestation of the poorer soils."

In a great measure, the opposition to the use of fertilizers in forest nurseries had developed because of theories which discounted the importance of nutrients for the growth of forest plantations and nursery stock. These ideas were based on misinterpeted observations of some mature productive forest stands growing on soils with an apparently low content of nutrients. The trees of such stands, growing widely spaced, are able to utilize nutrients from an enormous volume of soil; they store plant food in their leaves and return it to the soil as leaf litter. In this way a forest stand with its revolving fertility not only maintains an adequate supply of nutrients but over a long period may convert barren soil into productive land. Nursery stock, on the other hand, is grown at a great density; its roots seldom penetrate below a 10-inch depth; no crop residues are left in the soil of the nursery, because even the root systems are removed. As American experience of the past quarter of a century, involving production of billions of seedlings, has shown, the maintenance of a satisfactory fertility level in nursery soils usually requires applications of fertilizers at much higher rates than is common in farming practice.

FERTILITY STANDARDS OF NURSERY SOILS

Nutrient requirements of field crops are usually established on the basis of greenhouse pot cultures or sample plot trials. Both of these methods are very helpful in solution of many nursery problems, but they are not entirely suitable for the determination of appropriate fertility levels required by nursery stock of different tree species.

The farmer grows his crops for consumption, and he is interested primarily in pounds or bushels of his produce. The forester raises his seedlings not for consumption but for the struggle against adverse influences of environment, parasitic organisms, and browsing animals. Therefore, the quantitative criteria of agriculture, suggested by Baulé and Mitscherlich (Mitscherlich, 1923), are not only inapplicable to nursery stock but may lead to disastrous results. Seedlings of maximum weight produced by heavy applications of fertilizers usually have succulent tissues, unbalanced top-root ratio, and other unsatisfactory properties which lower their ability to survive on cut-over lands (Fig. 12–1).

The wrestling with the problem of nursery soil fertility would have made slow progress had not Hilgard shown a short cut to its solution. In his text on soils (1906), this scientist warned against "futile attempts to deduce practically useful results from the chemical analysis of soils long cultivated, without first studying the less complex phenomena of virgin soils." As the key to the solution of fertility problems Hilgard advocated the investigation of soils supporting various types of native vegetation which he considered to be the concrete expression of the entire complex of growth factors.

Following Hilgard's line of reasoning, during the past years numerous soils supporting natural reproduction of different species were subjected to detailed analyses (Wilde, 1938; Wilde and Patzer, 1940; Wilde, 1946; Youngberg and Austin, 1954). The mean values of these determinations, representing the average condition of natural seedbeds, were adapted as standards for the maintenance of fertility

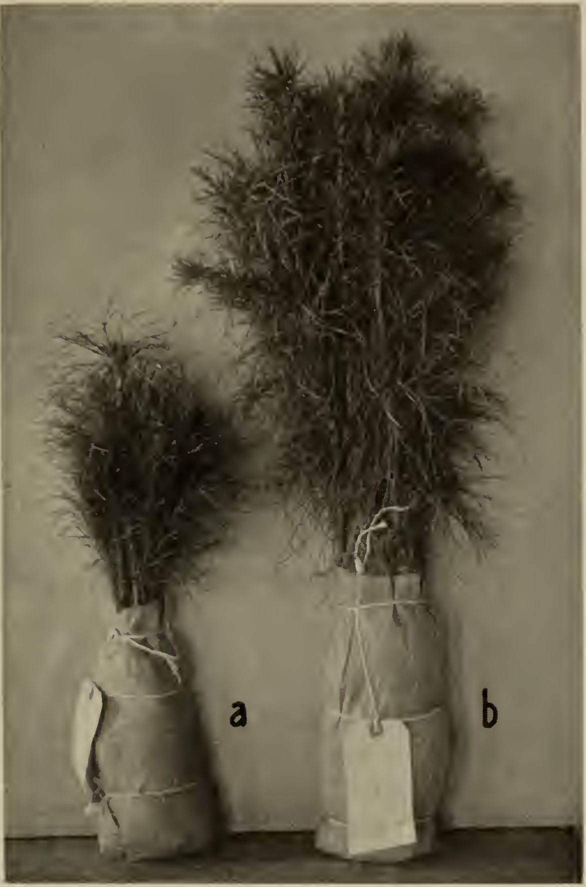


FIG. 12–1. An example of fertilizer-induced gigantism of jack pine seedlings: (*a*) large-sized 2-year-old seedlings raised on a fertile nursery soil; (*b*) abnormal seedlings of the same age produced by unreasonably heavy fertilizer treatments, a stock totally unsuitable for field planting because of its size, unbalanced top-root ratio, and high degree of succulence. (Courtesy of F. G. Kilp.)

in nursery soils. Table 12–1 gives the approximate contents of nutrients and the state of associated fertility factors for the three groups of tree seedlings characterized by varying requirements. As many years' experience has shown, these standards facilitate the production of normally developed nursery stock possessing a high survival potential.

In the great majority of cases the adjustment of soil fertility to the desired optimum level cannot be accomplished by a single application of fertilizing material but by systematic annual analyses of nursery soil and by gradual adjustment of fertility factors. In carrying out such adjustments, the forester must have full appreciation of the merits as well as the shortcomings of the contemporary methods of soil analysis, particularly those concerned with available nutrients.

TABLE 12–1

Soil Fertility Standards for Raising Nursery Stock of Different Nutrient Requirements

Soil-fertility rating	Range of reaction (pH)	Exchange capacity (m.e./100 g.)	Total N (%)	Available P_2O_5 (lb./acre)	Available K_2O (lb./acre)	Exchangeable Ca (m.e./100 g.)	Exchangeable Mg (m.e./100 g.)
Grade A	5.5–7.3	10.0	0.20	100	250	5.0	2.0
Grade B	5.0–6.0	7.0	0.12	70	200	2.5	1.0
Grade C	4.8–5.5	4.0	0.07	25	100	1.5	0.5

Grade A. High level of nursery soil fertility corresponding to requirements of exacting hardwoods and some lime-demanding conifers, such as black walnut, pecan, white ash, white oak, tulip poplar, hard maple, basswood, wild crabapple, highbush cranberry, and white cedar. This state of soil-fertility factors may be harmful to species of low nutrient requirements, especially those predisposed to damping-off disease.

Grade B. Moderate but stable level of soil fertility satisfactory for the majority of conifers and for less-exacting deciduous species, e.g., white spruce, white pine, Douglas fir, yellow birch, northern red oak, largetooth aspen, black cherry, mountain ash, and hawthorn.

Grade C. Low and unstable level of soil fertility satisfactory only for pioneer pines, such as jack pine, Virginia scrub pine, Scotch pine, and other species of very low nutrient requirements.

At the present there is no laboratory procedure which can detect the fractions of various nutrient elements actually available to plants, for the leaching of a soil sample with an extracting solution of any composition and strength cannot duplicate the complex biological mechanism of a root hair or mycorrhizal mycelia. Therefore, an analysis indicating critical levels of certain elements, for example, 10 pounds of phosphorus and 50 pounds of potassium per acre, may or may not be trustworthy. This is especially true of trees and other woody plants whose mycotrophic organs are capable of extracting nutrients from difficultly soluble mineral and organic compounds. On the other hand, long experience has provided convincing evidence that at a certain level of nutrient elements, extractable with solutions of definite concentration, the plants do not experience their deficiency. Thus, if analysis of a nursery soil reveals 50 pounds of available phosphorus or 200 pounds of available potassium per acre, there is a nearly absolute assurance that the stock of pine species will not experience a shortage of these elements during the next growing season.

In the management of nursery soils the greatest value of soil analysis rests in its ability to serve as a yardstick of nutrient content present in natural seedbeds and in nursery beds.

The use of virgin forest soils as the basis of soil analysis has another highly important advantage. At this time there is no uniformity throughout the world or even in individual countries as to the procedures employed in the determination of available nutrients. Because of the differences in the nature and strength of extracting solutions, satisfactory contents of nutrient elements, as determined by different laboratories, may vary 200 or 300 per cent. Nevertheless, if the employed analytical procedure is scaled on the basis of virgin soils of definite productivity ratings, the results of determinations usually preserve their practical significance.

It is not the recent progress in the technique of analytical determinations of soil fertility factors that helped the materialization of Hilgard's ideas; as far as forestry practice is concerned, it is the ideas of Hilgard that helped to remove soil analysis from the realm of mere speculation and convert it into a tool of immense practical usefulness.

ANALYSIS OF NURSERY SOIL AND CORRECTION OF VARIOUS FERTILITY FACTORS

Analysis of a sufficient number of soil samples is the first step toward adjustment of the nursery soil fertility. Depending on conditions of topography, soil, and stock, the required number of samples in a 40-acre nursery may vary from twenty to sixty. Each sample constitutes about seven 6-inch cores removed with a sampling tube three-quarter inch in diameter. All of these sample cores should be collected from an area of a single square yard; the wide dispersion of individual samples may erase the drastic differences in the composition of the soil and provide average data of soil fertility factors which do not exist in reality. A map or a sketch of the nursery indicating the location of sampled beds is another prerequisite to a planned soil management. The sampling is accompanied by a recording of general soil conditions, previous fertilizer and biocide treatments, and the nature and quality of nursery stock. In some cases soil sampling is supplemented by sampling of stock for foliar and other analyses.

Correction of soil reaction. The acidification of soil is accomplished by the application of acid peat, sulfur, aluminum sulfate, or acid-forming fertilizers, such as ammonium sulfate and ammonium nitrate. A decrease in acidity is achieved by the use of lime, wood ashes, organic remains high in bases, or alkali-forming fertilizers, particularly sodium nitrate. In all these treatments it is necessary to consider not only the pH value of the soil but also its colloidal content and capacity to neutralize acids and alkalies. The determination of the total alkalinity, total acidity, and the neutralizing capacity of the soil (Patel and Truog, 1952; Wilde and Voigt, 1955) facilitates the determination of the amount of acidifying or alkali-forming materials needed. In many cases, however, the rate of application of these materials is determined by empirical sample plot trials or treatments of potted soil samples. The results of such trials are determined after a period of several weeks when the acidifying or neutralizing reactions are completed. The less drastic alterations of the pH value of soils are accomplished gradually by the combined use of suitable buffering and fertilizing materials. Radical changes of soil reaction require the use of lime and sulfur or aluminum sulfate.

Adjustment of the exchange capacity. The increase in the exchange capacity is usually achieved by application of organic remains, chiefly peat. The amount of buffering material needed (M) is calculated from the following formula:

$$M = \frac{S(d\text{-}a)}{m}$$

where S is the weight of the root-bearing layer of soil per acre, d the desired and a the actual exchange capacity of the soil, and m the exchange capacity of the material to be applied.

Suppose the exchange capacity of a nursery soil raising stock of exacting hardwoods is 7 m.e. per 100 g., and the desired capacity is 10 m.e. per 100 g. If the furrow slice of the soil is 2,400,000 per acre, and the available peat has a capacity of 120 m.e. per 100 g., the amount of peat to be applied would be: $2{,}400{,}000 \times (10 - 7) \div 120$, or 60,000 pounds per acre. This corresponds roughly to 120 cubic yards or 20 large truckloads per acre.

Where there is a suitable deposit of clay in the proximity of the nursery, it may be used instead of peat. The chief advantage of using clay is its stability in the soil, but clays of high exchange capacity and suitable reaction are of rare occurrence.

Increase of the soil nitrogen content. The adjustment of the base exchange capacity by application of organic remains usually brings the content of the total nitrogen to the desirable level. If not, this is accomplished by the addition of peat. The amount of peat required to correct the deficiency is calculated by the use of the formula given for exchange capacity. Suppose the total nitrogen content of the nursery soil is 0.07 per cent and the desired content is 0.12 per cent. If the surface soil layer weighs 2,400,000 pounds per acre and the available peat analyzes 2.5 per cent of the total nitrogen, the amount of peat to be applied is:

$$\frac{2{,}400{,}000 \times (0.12 - 0.07)}{2.5}$$

or 48,000 pounds, or about 100 cubic yards of peat per acre.

Correction of the deficiency of available nitrogen. Under conditions of well-aerated soil, adequately supplied with organic matter, microorganisms provide a sufficient amount of available nitrogen by converting protein-like compounds into nitrates and ammonia (Russell, 1950). The usual release of the nitrate and ammonia nitrogen in nursery soils constitutes about 1 per cent of the total nitrogen, or about 40 or 45 pounds per acre per year if the soil analyzes 0.2 per cent of the total nitrogen. Under such conditions there is no need to apply soluble nitrogen fertilizers.

In many instances, however, the content of available nitrogen released by soil organisms is not sufficient because of crowded seedbeds, presence of organic remains of a high C/N ratio, intensive leaching by rains and artificial watering, or a suppressed microbiological activity. The latter condition may be particularly expected in nursery soils treated with eradicants. In all such cases the content of available nitrogen should be augmented by application of ammonia or nitrate fertilizers.

There is no simple procedure for the determination of the exact amount of mineral nitrogen fertilizer to be applied, since this depends upon a great variety of factors. Fortunately, deficiency of nitrogen is readily manifested by discoloration of foliage, and consequently, the application of nitrogen fertilizers is usually dictated by the appearance of the stock. A good rule to follow in nitrogen fertilization is to apply too little rather than too much. A deficiency may be corrected by a second application; an excess produces planting stock lacking in vigor.

As analyses of virgin soils and nursery experience have indicated, the state of available nutrients (N-P_2O_5-K_2O) should approach the ratio of 1-2-5 or 1-3-5, if vigorous, well-balanced stock is to be produced. This means that in soil with 80 pounds of available phosphorus pentoxide and 200 pounds of available potash, the maximum single application of nitrogen fertilizer should not exceed 40 pounds of elemental nitrogen, or 200 pounds of 20 per cent ammonium sulfate, or an equivalent amount of any other nitrogen fertilizer. An application higher than 60 pounds of elemental nitrogen would seldom be justified.

Correction of phosphorus deficiency. A deficiency of available phosphorus is corrected by the application of phosphate fertilizers. If a soil analyzes 30 pounds per acre of available phosphorus pentoxide (P_2O_5) and the desired content is 80 pounds, the deficiency of 50 pounds may be supplied by an addition of about 100 pounds of 45 per cent treble superphosphate or 250 pounds of 20 per cent superphosphate.

Correction of potassium deficiency. A deficiency of available potash is corrected by a method similar to that for phosphorus. For instance, if the soil content of available potash (K_2O) is 100 pounds and the required amount is 200 pounds per acre, the deficiency of 100 pounds is met by the addition of 200 pounds of 50 per cent muriate of potash or sulfate of potash.

Correction of calcium and magnesium deficiencies. A critically low content of magnesium and especially calcium is confined to comparatively rare instances of strongly acid nursery soils. In many instances the deficiency of these elements may be safely corrected by the addition of organic remains high in bases. Peat and forest litter possessing a high base content are not necessarily of an alkaline reaction, and hence their application to nursery soils does not involve the danger of encouragement of parasitic fungi. Within certain limits the addition of low-grade phosphate fertilizers and magnesium sulfate or potassium-magnesium sulfate may contribute to the correction of calcium and magnesium deficiencies. In extreme cases the deficiencies must be remedied by application of dolomitic limestone.

Soil improvement program. Ordinarily, soil improvement involves a period of several years and follows a definitely outlined program. The length of time needed for soil-building depends on a number of factors, such as present condition of soil in relation to the desired state, species of trees being grown, and availability of funds. Experience has shown, however, that most soils can be brought into a fully productive state in the course of three 2-year rotations.

In outlining a soil improvement program it is important to keep in mind the relationship that exists between the total soil fertility, the fraction of nutrients in the soil solution, and the content of nutrients actually required by seedlings during their one- or two-year period of growth. The amount of nutrients necessary for the actual annual metabolism of forest seedlings constitutes, as a rule, but a small fraction of the total available supply of nutrients present in a productive nursery soil. For example, the amount of calcium taken up by a crop of even caliphilous hardwood seedlings is much less than 1 m.e. per 100 g., or 400 pounds per acre (Stone, 1940). Nevertheless, a productive hardwood nursery soil must contain at least 5 m.e. per 100 g. of replaceable calcium, or 2000 pounds per acre. The presence of this high amount is vital because calcium fulfills numerous functions in soil besides that of a plant nutrient; it regulates reaction, counteracts the toxicity of other ions, and stimulates the activity of microorganisms.

In nursery soils, exposed to rainfall and artificial irrigation, the content of soluble nutrients is subject to frequent changes. During a period of abundant rainfall the readily soluble salts are leached away, and the soil is saturated with nearly pure water. After the rains have stopped, hydrolysis and activity of microorganisms release additional nutrients into the soil solution from minerals, exchange material, and organic compounds, that is, from the storehouse of the plant nutrients (Truog, 1938). The higher the reserve supply of nutrients, the more stable is the level of the readily available fraction and the greater is the assurance of an uninterrupted and balanced nutrition of seedlings.

In recent years the science of plant nutrition has been broadened by a number of remarkable achievements: nearly dead plants were revived by colloidal suspensions of certain metals; the growth of roots on twigs of conifers was promoted by the use of hormones; high yields were produced in soil-less cultures; many improvements were obtained through the use of trace elements and inoculations with nitrogen-fixing bacteria, mycorrhizal fungi, and earthworm cultures. Unfortunately, not all of the new developments enjoy as yet a full success under actual nursery conditions. To a great extent this is because the applications of new treatments are not always preceded by a careful adjustment of primary soil fertility factors. It is obvious that no hormones, colloids, or microorganisms can improve the growth of stock if the soil is deficient in phosphorus, potassium, or any other essential nutrient element.

REGULATION OF ARTIFICIAL IRRIGATION

The regulation of artificial irrigation is an essential part of maintenance of soil fertility. Under proper management artificial watering facilitates the preservation of stock during periods of prolonged drought and makes possible the retention of an adequate and uniform content of soil moisture. Indiscriminate use of irrigation, however, may cause serious damage to soil fertility and promote the deterioration of seedlings. Excessive watering creates an anaerobic condition, leaches or renders unavailable plant nutrients, and encourages the development of fungus diseases. Besides these direct detrimental effects, excessive watering may be harmful by developing succulent seedlings vulnerable to injuries by drought and frost.

Rate of watering. Most practical foresters adhere to the philosophy that it is better to lose the weaker specimens in the nursery than to raise the stock on excessive moisture and have subsequent large-scale failures of trees planted in the field. In spite of this, even nurserymen who intend to minimize watering often apply considerably more water than seedlings actually need.

In order to establish a reliable control of watering, it is necessary to record the quantity of applied water and to relate this quantity to the average monthly rainfall. For this purpose the nursery should be equipped with a number of rain gages, placed inside and outside of the region of artificial irrigation. In a conservative watering, the amount of water added to the soil each month should not greatly exceed the average monthly rainfall. A cursory survey showed that in some nurseries, four to five times as much water as the average precipitation for the same period was added during two dry months. Thus in some instances, artificial irrigation has in effect translocated the nursery from the prairie-border region of the central United States to the extremely humid climate of the Pacific Coast.

In fine-textured nursery soils the establishment of a proper rate of watering may be materially facilitated by an analysis of the physical properties of the soil. A knowledge of soil aeration is particularly significant since it is a function of two variable factors—the degree of water saturation and soil porosity. Consequently, soil aeration data have the same general significance for all soil types. As long as watering does not lower the aeration of soil below 20 per cent by volume for any considerable length of time, there is no danger of denitrification and other reduction processes. This means that satisfactory conditions for the growth of trees on soils having a porosity of 50 per cent may be maintained with as much as 30 per cent of water by volume. On the other hand, with soils having a porosity of 40 per cent, only about 20 per cent of water is permissible. The aeration of coarse sandy soils practically never drops to an undesirable level.

In dry seasons it is advisable to dig into the soil periodically to a depth of about 1 foot in order to ascertain either by laboratory methods or ocular estimation the penetration of soil moisture and probability of drought. The maintenance of a proper water supply also may be facilitated by the use of resistance blocks or tensiometers.

Time and manner of watering. Ordinarily, light, frequent sprinkling is not so effective as prolonged application of water at longer intervals. Light sprinklings wet only the upper 1 or 2 inches of soil, and a large amount of water may be rapidly lost through evaporation from the soil surface. In some cases, however, frequent light watering may be advantageous. Only a limited amount of water may be applied at a time on heavy soils when there is danger of denitrification. A certain amount of care is needed in watering soils of low colloidal content which have been treated with soluble commercial fertilizers, as these may be washed out. A careful periodic examination of the development of root systems and penetration of water on a given soil type is essential to the establishment of a proper rate of watering.

There has been a long, unsettled argument as to the effects of water applied on hot days under direct sunlight. While many nurserymen claim that this practice is harmful to seedlings, others deny the validity of this belief. Watering on days of scalding temperature decreases the air and soil temperature and often prevents the destruction of stock by heat. At the same time, this practice is not economical, because rapid evaporation prevents the penetration of water to any great soil depth. The most efficient use of water is obtained when it is applied late in the evening. Such a practice allows the percolation of water to a depth of 8 or 9 inches. Thus, when the temperature becomes high in the middle of the day, the water is protected from evaporation by a soil layer of considerable thickness. The application of water in the early morning, from three to five o'clock, is almost as efficient as evening watering. As observations showed, in nurseries where water was applied during the evening and early morning hours, including nurseries without an overhead system, no losses of stock occurred in the extreme drought of 1936 in the Lake States region.

Watering in the daytime is decidedly harmful when the nursery is using hard water, because the increased evaporation promotes the formation of a crust of calcium and magnesium carbonates. Although such a crust rarely attains a thickness of more than one-eighth inch, it may cause the deterioration of stock. One-year-old seedlings are particularly susceptible to injury of this kind.

As a protection against frost injury, the operation of the overhead system may become urgent during late spring and early fall nights when the temperature drops suddenly toward the freezing point.

APPRAISAL OF THE QUALITY OF PRODUCED NURSERY STOCK

The soils of permanent nurseries often present delicately balanced and rather dangerous hydroponic-like media loaded with high-grade synthetic fertilizers, systemic poisons, growth inhibitors and growth promotors, oil sprays, aerosols, and toxic gases. The combined effect of all these chemicals may easily upset the balance of available nutrients and in turn produce anatomical and physiological abnormalities of plants decreasing their vigor and growth potential. Because such abnormalities are not always reflected in gross morphological features, nursery stock quality is appraised either by empirical field performance trials or by laboratory analysis (Shirley and Meuli, 1939; Erdtman and Rennerfeldt, 1944; Němec, 1948; Vavilov, 1950; Lundegårdh, 1951; Wakeley, 1951; Wilde and Voigt, 1955).

FIELD TRIALS

The old saying, "The proof of the pudding is in the eating," is well applicable to nursery practice. Careful observation of the field survival and the rate of growth of nursery stock, produced under different methods of soil management, still remains the most reliable measure of the stock quality.

As far as possible, the stock subjected to field trials should be planted on sites exposed to drought and frost. The success of such trials depends in a large degree upon the uniformity of the soil of the test area and the use of randomized plots in a number assuring statistical significance of the results. As a rule, sandy soils of glacial outwash or river terraces provide ideal testing grounds. Long, randomized strips of seedlings, hand- or machine-planted across the entire test area, are by far preferable to isolated square plots. The trials should include control stock produced on small areas of cleared virgin forest land or on a nursery block whose fertility is maintained by periodic additions of litter or leaf mold from a productive forest stand. Tables 12–2 and 12–3 present some results obtained under field conditions with variously fertilized nursery stock.

ANALYSIS OF NURSERY STOCK

In order to avoid, or at least to reduce, the time-consuming appraisal of the nursery stock quality by field tests, the soundness of nursery soil management can be verified by systematic analyses of produced

TABLE 12-2

Survival and Height Growth of Two-Year-Old Jack Pine Raised on Beds of an Average Fertility and Those Treated with a High-Rate Application of Complete Fertilizer. Results Recorded Three Years After Planting Seedlings in the Field (After Wilde, Wittenkamp, Stone and Galloway)

Plat	Unfertilized stock Survival (%)	Unfertilized stock Height (in.)	Fertilized stock Survival (%)	Fertilized stock Height (in.)
A	73.0	24.9	91.0	37.0
B	83.0	22.7	87.0	27.4
C	92.0	20.9	89.0	26.6
D	63.0	25.9	86.0	25.0
Average	77.8	23.4	88.3	29.4

Average increase in survival: 88.3 − 77.8 = 10.5 per cent.
Average increase in height growth: 29.4 − 23.4 = 6.0 inches.

TABLE 12-3

Effect of Complete N–P–K Fertilizer and Acid Peat Applied Broadcast upon Survival of 1–0 Jack Pine Seedlings (Adopted from Technical Notes of the Lake States Forest Experiment Station, No. 162, 1940)

Nursery treatment per acre	Classification of nursery stocks *			Field survival (%)
	Plantable (%)	Good (%)	Excellent (%)	
1. No treatment	60	12	7	69.6
2. 400 lb. 20% ammonium sulfate, 600 lb. 20% superphosphate, 160 lbs. 50% potash	95	22	12	70.7
3. Same as No. 2 plus 20 tons of peat (oven-dry basis)	100	67	47	77.0

*In classifying nursery stock, trees of $^{4}/_{64}$-inch caliper and over are considered plantable; those $^{5}/_{64}$-inch and over are good; those $^{6}/_{64}$-inch and over are excellent.

seedlings. Such analyses will, in the long run, help in detecting the shortcomings in the method of stock production and will alleviate differences of opinion between the nursery manager and forestry personnel in charge of tree-planting. Because of economic aspects, such analyses should be confined largely to stock produced on blocks which appear to be depleted in nutrients and blocks treated with heavy applications of fertilizers or biocides. Because the dimensions and the internal properties of seedlings vary during the growing season, it is best to conduct the appraisal of stock when the trees have entered the period of dormancy. The following outline presents a brief summary of the less-complicated analyses of the morphological and physiological properties of seedlings that deserve primary consideration.

Color of stock. The color of foliage frequently furnishes clues to critical deficiencies of certain nutrients, the presence of toxic substances, and injury by climatic extremes or parasitic organisms (Hambridge, 1941; Kitchen, 1948; Wallace, 1951). Although the color is one of the most conspicuous characteristics of seedlings, its exact recording has encountered considerable difficulty because of the combined effect of the three basic features responsible for the phenomenon of color—hue, value, and chroma. Fortunately, the task of color determination is facilitated by the standard charts, such as Munsell notations, which express color in terms of concrete formulas (Wilde and Voigt, 1952).

The use of such charts in appraisal of nursery stock may be illustrated by the following examples: Seedlings produced on soils of a low fertility level, particularly soils deficient in nitrogen, are characterized by greenish-yellow color of leaf tissue ranging from 2.5 GY: 8/4 to 2.5 GY: 8/10. Deep-green to blue color of foliage, approaching 2.5 B: 3/6, indicates an undesirably high content of nitrogen and stock by questionable vigor. Red-purple color, 5.0 RP: 4/2 to 4/8 and 3/6 to 3/10, revealed by part of needles or leaves, is usually a sign of an acute deficiency of phosphorus, whereas brownish-yellow color, 5.0 Y: 8/6 to 8/8 and 7/6 to 7/10, is indicative of a potassium deficiency. A pronounced yellow color, 5.0 Y: 8/10, is often the result of magnesium deficiency. An excess of soluble salts or a presence of toxic compounds produces a yellowish-green or gray-green color which is eventually changed to red, 5.0 R: 7/4 to 3/10. Stock produced on a well-balanced diet with a moderate amount of available nitrogen, which is well adapted to planting on adverse sites, is characterized by slightly yellow or grayish-green shades, ranging from 7.5 GY: 6/4 and 6/10 to 2.5 G: 7/4 and 7/6. Any deviation from the normal color of foliage points out some abnormality of seedlings caused by nutritional, climatic, or biotic factors.

Height and diameter of stock. A 4-foot ruler with ten equally spaced notches is laid across the nursery bed, and the ten seedlings nearest to the notches are cut by means of clippers. The ruler bears a scale calibrated in centimeters on which each seedling is measured.

The sum total of all the measurements divided by the number of seedlings gives the average height. Ordinarily two ruler samples, or twenty plants, are sufficient to determine with a reasonable degree of accuracy the average height of stock on a standard 4 × 12 foot nursery bed.

Following the determination of average height, the diameter of sampled seedlings is measured near the crown line by means of a precision caliper graduated in millimeters. The sum of all diameters divided by the number of measurements gives the average diameter of stock.

Besides serving as a direct expression of soil fertility level, the average height and diameter provide an extremely important feature of nursery stock, its relative morphological development expressed by the height-diameter ratio. The average height in centimeters divided by the average diameter in millimeters gives the **height-diameter quotient**, which is closely related to the stability of seedlings against lodging and suppression by competing vegetation. For most two-year-old coniferous seedlings an h/d quotient exceeding 7 indicates spindly stock, raised in crowded seedbeds, which is likely to be inferior planting material.

In certain nurseries, or nursery blocks, it may be desirable to use height measurements for calculation of the **coefficient of variability**, according to the following formula:

$$Cv = \frac{\sqrt{\frac{(x-h)^2}{n-1}} \cdot 100}{h}$$

where x is the height of individual seedlings, h is the average height, $(x-h)^2$ is the sum of squared differences, and n is the number of measured seedlings.

Although the coefficient of variability is greatly influenced by the inherent properties of different tree species, its high values exceeding 10 to 15 reveal lack of uniformity of produced stock resulting from poor distribution of fertilizing materials, critical level of biocide treatments, or heterogeneous origin of seed (Fig. 12–2). As often as not, a low coefficient of variability reflects the careful management of both nursery soil and nursery stock.

Specific gravity of seedling stems. Few analyses of nursery stock can compare in their simplicity and direct value with determinations of the specific gravity of seedlings. According to Büsgen and Münch (1929), "specific gravity determines the strength of wood, its resistance to breakage, elasticity, and durability." The damages of seed-

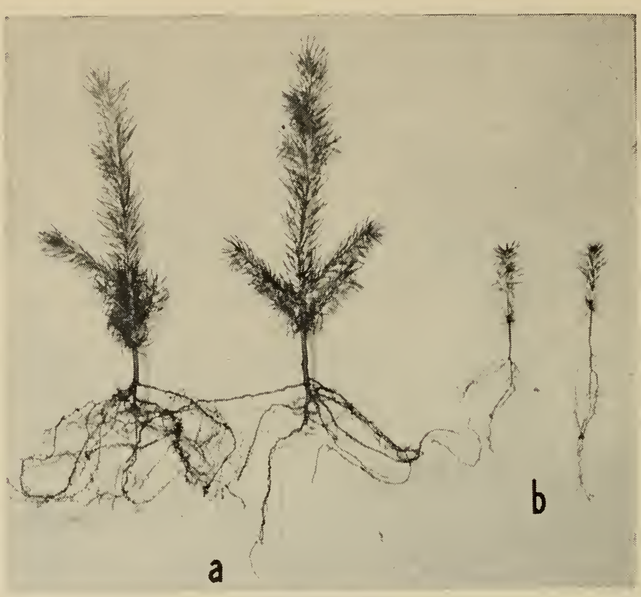


Fig. 12–2. Rate of growth of Norway spruce seedlings of different genetic origins, raised simultaneously under controlled conditions: (*a*) average seedlings raised from seed probably of Austrian origin collected in southern Wisconsin; (*b*) average seedlings raised from seed collected in central Sweden. (After Youngberg, 1951.)

lings by snowpress, sleet, hail, rain, and wind, either in nursery beds or on cut-over lands, are most severe when seedlings have weak stems of a low specific gravity. Moreover, a low specific gravity of plants reflects their succulent nature and often indicates an impaired resistance of stock against drought, frost, and parasitic organisms. With no exception, nursery stock of subnormal specific gravity is the result of the nursery mismanagement and especially the faulty maintenance of soil fertility (Fig. 12–3).

In rare cases, a low specific gravity is caused by starvation of seedlings, leading to an underdevelopment of the pith. As a rule, however, this is the consequence of excessive application of fertilizers, particularly nitrogen salts, which leads to the thinning of cell walls. In some instances excessive treatments of soil with ammonium nitrate have decreased the average thickness of cell walls of jack pine from 2.6 to 1.5 microns and the specific gravity from 0.41 to 0.23 (Fig. 12–4).

The specific gravity of stems, as understood in analyses of nursery stock, is the ratio of the oven-dry weight of wood to its original green volume (Wilde and Voigt, 1948). The volume is determined on a sample of ten to twenty stems by means of the Bruil volumeter or

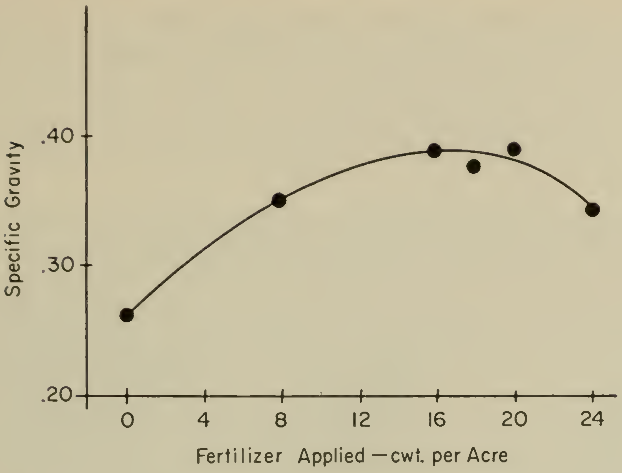


FIG. 12–3. Effect of monoammonium phosphate and potassium nitrate fertilizers on the specific gravity of year-old white ash seedlings grown in subirrigated cultures. Each point represents the average of nine determinations. (After G. K. Voigt, 1949.)

other mercury volumeter. The weight of stems is taken after they are dried for two hours at 105° C. The determination of specific gravity and other properties of nursery stock are made on seedlings of average heights.

Top-root ratio. Samples of seedlings are dried in the oven at 105° C., and the weights of crowns and roots in grams are determined separately, preferably by the use of a dietetic balance. The calculated top-root ratio expresses the morphological balance of

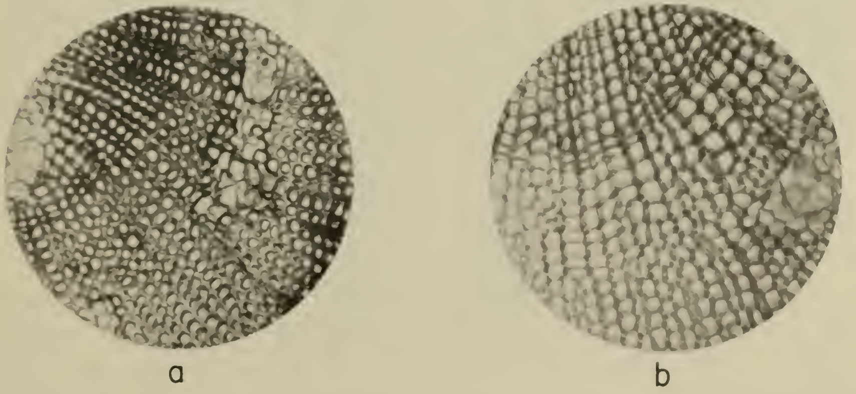


FIG. 12–4. Transverse sections of stems of two-year-old jack pine seedlings raised on soils with different levels of fertility: (*a*) seedling naturally reproduced on a coarse sandy outwash; (*b*) seedling grown on a nursery bed treated with 600 pounds of ammonium nitrate per acre. (After G. K. Voigt, 1949.)

seedlings and often indicates seedlings' ability to counteract the transpirational losses of crowns by the absorbing capacity of root systems. In many trials T/R ratio proved to be significantly correlated with the ability of seedlings to withstand drought and is a widely accepted criterion for evaluation of nursery stock (Fig. 12–5).

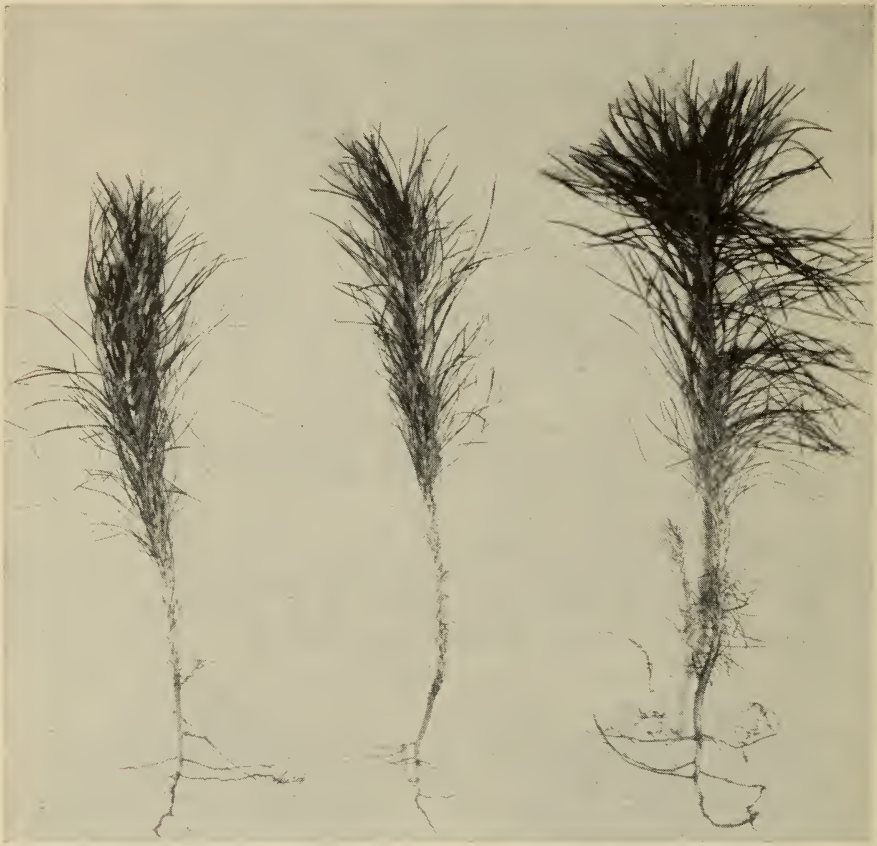


Fig. 12–5. Two-year-old jack pine seedlings of extremely unbalanced top-root ratio, a drought- and frost-vulnerable product of mismanaged nursery soil. (After G. K. Voigt, 1951.)

Titration value of root systems. In certain types of nursery stock, the top-root ratio is not too reliable an indicator of seedlings' quality (Bauer, 1911; Roberts and Struckmeyer, 1946). This is especially true of seedlings which develop heavy lateral roots with very few fibrous rootlets and mycorrhizal short roots. Therefore, a truer picture of the adsorbing capacity of roots is obtained by saturation of a representative sample of roots with 0.3 N HCl and titration with

0.3 *N* NaOH. The adsorbing capacity of the root is then expressed in milliliters of titration, calculated per seedling.

In some detailed investigations of nursery stock, the evaluation of the adsorbing capacity of roots may be supplemented by the determination of the transpiration losses of crowns in a special chamber with preheated forced air (Wilde and Voigt, 1949). The titration value in milliliters divided by transpirational loss in grams gives the **adsorption-transpiration quotient**, a more exacting equivalent of the top-root ratio.

Chemical composition of stock. The determination of the content of nutrient elements in the foliage is too laborious to be employed

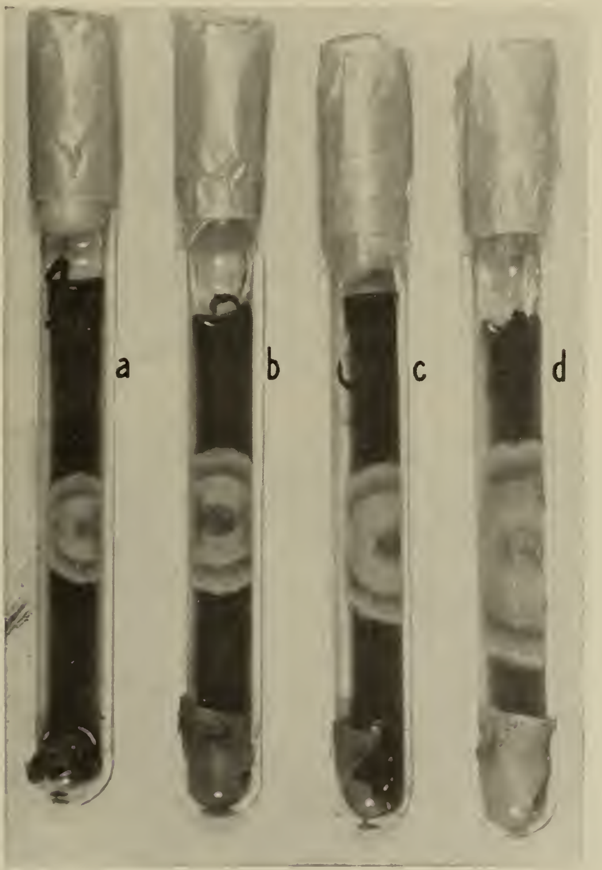


FIG. 12-6. Depressing effect on jack pine root extract on the growth of mycelium of a parasitic fungus, *Polyporus schweinitzii,* in malt agar cultures: (*a*) high concentration of root extract equal to 3.5 per cent; (*b*) concentration of 2.5 per cent; (*c*) concentration of 2 per cent; (*d*) low concentration equal to 1 per cent. (After D. P. White, 1950.)

in routine appraisal of nursery stock. Nevertheless, such determinations are essential when the color of foliage or other characteristics indicate a serious discrepancy in the ratio of nutrients due to an actual depletion of certain elements or the presence of harmful compounds which convert nutrients to unavailable form. In such cases the foliar analysis is performed largely for the purpose of detecting the existing nutrient deficiency. Usually the ratios of different elements, particularly N, P, K, Ca, and Mg, are of greater indicative value than their absolute contents.

A single chemical characteristic of seedlings which reflects conspicuously the level of soil fertility, and especially the harmful effect of excessive nitrogen, is the content of alcohol-benzine soluble substances including resin acids, resins, and tannins. A low content of organosolubles results from their "dilution" by carbohydrates produced by plants at unreasonably high rates under conditions of an abnormally rapid growth. There is a probability that the content of resins, tannins, and related "antiseptic" compounds has a bearing upon the resistance of seedlings against parasitic organisms (Offord, 1940; Erdtman and Rennerfeldt, 1944; Zabel, 1948). Figures 12–6 and 12–7 illustrate the protective effect of the cell sap of different concentration and composition. Because the determination of organosolubles involves the use of highly inflammable extracting substances, it must be confined to a specially equipped laboratory under expert supervision (Wilde *et al.*, 1948).

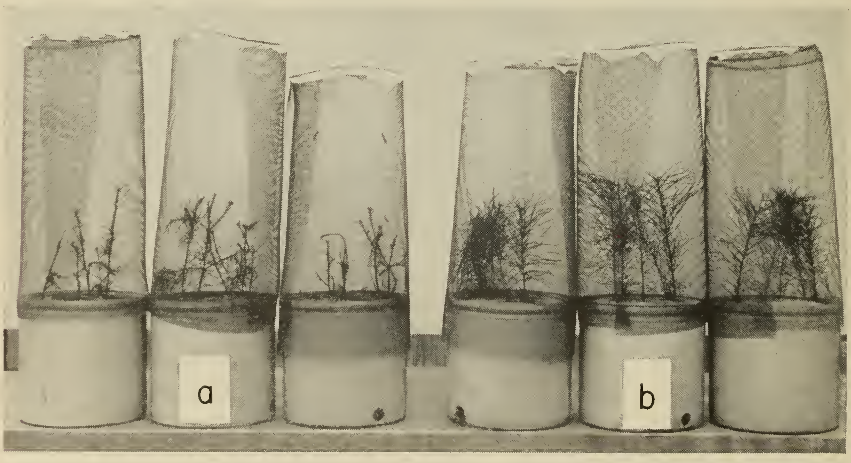


Fig. 12–7. The fate of seedlings of different origin attacked by red-headed pine sawfly larvae, *Neodiprion lecontei*: (*a*) jack pine seedlings of natural reproduction completely defoliated; (*b*) fertilized nursery stock whose foliage poisoned larvae in the initial stages of feeding. All cultures were infested with 25 larvae of equal size. (After D. P. White, 1950.)

TABLE 12–4

Results of Analyses of Two-Year-Old Seedlings Produced Under Different Methods of Nursery Soil Management. Chemical Analyses Performed on Foliage. Results Per Average Seedling

Properties of stock	Jack pine		Red pine		White spruce	
	Nursery A	Nursery B	Nursery A	Nursery B	Nursery A	Nursery B
Color index (No.)	2.5GY 7/6	7.5GY 5/6	7.5GY 7/6	2.5G 5/4	2.5G 6/4	2.5G 5/6
Height (cm.)	15.90	27.40	6.90	10.10	6.40	13.30
Coefficient of variability	15.10	11.50	3.60	15.10	21.10	14.40
Stem diameter (mm.)	2.50	3.90	2.00	2.00	1.10	1.80
Height/diameter ratio	6.00	7.00	3.50	5.00	6.00	7.40
Dehydrated weight (g.)	1.90	3.80	1.10	0.90	0.80	1.30
Top-root ratio	5.30	8.50	2.60	3.50	2.90	4.30
Specific gravity	0.31	0.29	0.31	0.32	0.33	0.38
Root titration (ml.)	0.19	0.12	0.10	0.09	0.07	0.08
Transpiration loss (g.)	0.46	0.93	0.40	0.36	0.07	0.28
A/T quotient	0.41	0.13	0.25	0.25	1.00	0.28
Ash (%)	3.21	3.98	3.65	3.10	3.81	3.28
Phosphorus (%)	0.18	0.18	0.15	0.13	0.12	0.15
Potassium (%)	0.76	0.68	0.28	0.26	0.27	0.24
Calcium (%)	0.28	0.15	0.19	0.16	0.43	0.31
Magnesium (%)	0.09	0.11	0.13	0.13	0.13	0.13
Nitrogen (%)	1.90	2.34	1.80	1.76	1.20	2.31
Organosolubles (%)	24.90	20.10	27.90	22.30	35.10	31.00
Organosolubles/N ratio	13.00	8.60	15.50	12.70	29.00	13.40

Table 12–4 presents results of analyses of several types of seedlings which illustrate in concrete terms the otherwise evasive concepts of the "hardiness," "vigor," and "quality" of nursery stock.

During the past fifty years many silviculturists have attributed the failure of forest plantations to the mistreatment of seedlings in the nurseries, particularly to the succulent nature of planting stock raised on overfertilized nursery soils. Consequently, nurserymen often found themselves in a vicious circle; they could not produce seedlings of plantable size on nutrient-depleted nursery soils without application of fertilizers, and yet they produced inferior stock when they did apply fertilizers (Dengler, 1930; Leiningen, 1931; Němec, 1950). The analysis of the external and concealed properties of seedlings provides a guide which should lead reforestation from the blind alley and replace the gross morphological grading of nursery stock by physiological grading (Wakeley, 1951). The careful analytical appraisal of nursery stock is now more urgent than ever because of the use of biocidic compounds that exert depressing as well as harmfully stimulating effect on growing plants (Wilde, Voigt, and Persidsky, 1956).

It is not the pathogenic microbes, but the state of the infested organisms that counts.

—Claude Bernard

13

Control of parasitic organisms and noxious weeds

Until recently the artificial control of parasitic organisms and weeds in forestry was entirely confined to soils of forest nurseries. In the last decade, however, discovery of new hydrocarbon eradicants made it possible for a forester to launch an offensive against the harmful biotic agents in soils of plantations, fire lanes, and even partially cut stands.

It is too early to predict the final over-all result of the superimposition of new potent sources of energy on the biological processes of the earth. But one thing is certain: the deterioration of the land and the growing stock by eradicants can be prevented only by constant careful observation of the composition of the soil. The soil is the medium which has to absorb the chemical refuse after every clash of life with ions and molecules and to digest the end products of biological chain reactions set in motion by different treatments.

OCCURRENCE OF PARASITIC ORGANISMS IN NURSERY SOILS AND PRINCIPLES OF THEIR CONTROL

Records of over one hundred years of forest nursery practice include but few cases in which seedlings on recently cleared land were attacked by parasitic organisms. This suggests that in many instances the invasion of the nursery by parasites is a manifestation of exhausted soil fertility, unskilled fertilization, use of parasite-inviting green manure crops, excessive watering, or the building up of large populations of introduced parasitic organisms. Therefore, careful management of the nursery soil appears to be one of the first requirements in protection of nursery stock from diseases.

If preventive measures fail and parasites invade the nursery, all possible efforts should be made to suppress them by suitable biocidic treatments. In carrying out these treatments, it should be kept in mind that *the welfare of the seedlings is just as important as the destruction of the parasites.* Usually, measures of control destroy not only the parasitic organisms but also the useful population of the soil. Very often such measures decrease availability of plant nutrients and leave toxic residues. For these reasons, the reestablishment of the ruined fertility, through application of buffering materials, antitoxins, fertilizers, and cultures or debris bearing useful organisms, forms an essential sequel to disinfection treatments.

The phytopathological literature of today includes numerous methods for the control of soil parasites. Unfortunately, in devising various treatments sufficient consideration has not always been given to the effect of disinfectants on the forest seedlings under different soil conditions and in the presence of different fertilizers. As a consequence, the application of such treatments without a thorough examination of soil either may fail to eliminate the parasites or may

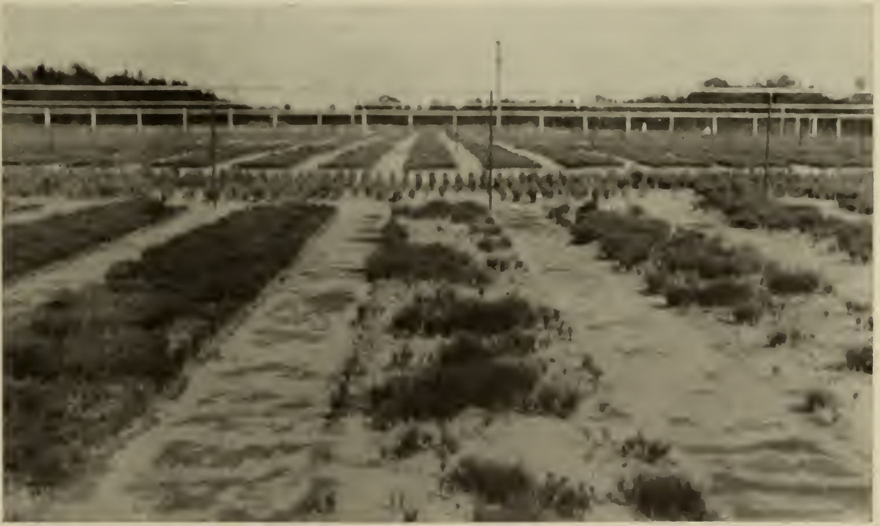


FIG. 13–1. Destruction of red pine nursery stock by damping-off fungi, largely *Rhizoctonia solani.*

produce a condition fatal to nursery stock. The reaction of the soil, content of colloids, organic matter, carbonates and exchangeable bases, petrographic origin of soil, and composition of soil solution are among the important factors which modify the kind, quantity, and concentration of the chemicals used in the control of parasites.

The most common and most dangerous parasites in nursery soils are the damping-off fungi, which cause the destruction of seedlings in their early period of growth (Fig. 13–1). Outstanding among these organisms are species of *Pythium, Rhizoctonia, Fusarium,* and *Phytophthora* (Boyce, 1948). Some of these fungi, particularly *Rhizoctonia* and *Pythium,* differ considerably in their habits and require a specialized approach to their control (Roth and Riker, 1943). The infected seedlings which do not succumb to the disease still reflect the aftermath of the fungus infection by their crippled morphology and inhibited growth (Ten Houten, 1939). In this respect damping-off disease produces consequences in plants not dissimilar to those of poliomyelitis in humans (Fig. 13–2). The destructive activity of damping-off fungi is sometimes supported by mites (*Arachnida* spp.) which appear to be instrumental in transmission of the infection. The disease may also be initiated or promoted by nematodes, particularly by species of *Iota* (Toumey and Korstian,

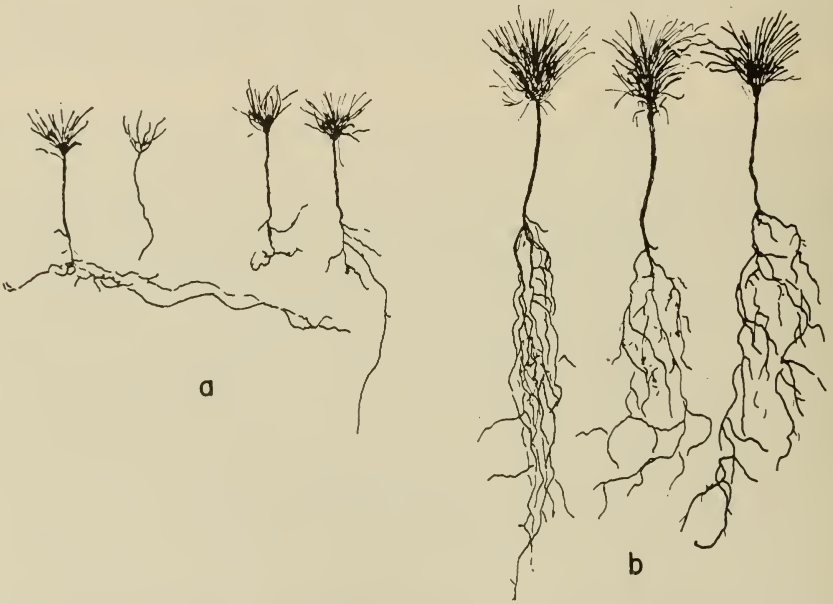


Fig. 13–2. Aftermath of damping-off disease as revealed by Scotch pine seedlings: (*a*) five-month-old seedlings which survived the disease. (*b*) Seedlings of the same age which were not attacked by damping-off fungi. (After Ten Houten, 1939.)

1947) and *Rhabditis* (Wilde, 1936), which have been found in the roots of injured seedlings of slash pine and red pine, respectively. Less conspicuous, but perhaps not less important, than damping-off fungi are their close relatives that cause the root-rot of older seedlings and transplants, particularly species of *Fusarium* and *Phytophthora* (Rathbun, 1922). Among the insect parasites, the white grub, *Phyllophaga*, root weevil, *Brachyrhinus*, and mole crickets, *Gryllidae*, should especially be mentioned (Graham, 1952; Metcalf and Flint, 1951).

The following discussion reviews the methods of parasite control commonly used in forest nurseries. The purpose of this outline is to give a cross section of the various approaches, and hence it includes methods of negative or dubious value in nursery practice.

SURFACE FIRING

The burning of brush, wood, or straw is the oldest and most primitive method of soil sterilization. Twenty centuries ago Virgil in his Georgics said, "Often you will find it well to burn the garnered field and set the flimsy straw a-cockling in the flames. Whether perchance the land in this wise finds some unknown force, or that every fault thereby is purified by fire and all the useless humours purged. . . ."

Although in some trials surface firing proved to be satisfactory as a means of damping-off control in forest nurseries, no conclusive results have been reported. Because wood ashes and the decreased acidity following burning may encourage the development of surviving damping-off fungi (Anderson, 1930), this method requires a careful investigation of its reliability under local conditions before it is used on a large scale.

STEAMING OF SEEDBEDS

Sterilization by steam may be found practicable under special conditions, but there has been only limited experience with this method in forest nursery practice (Scheffer, 1930). Sterilization of the soil by steam lowers the fertility because of the destruction of some useful organisms, breakdown of soil colloids, and excessive accumulation of soluble salts. Steaming has been advocated as a means of partial sterilization, a process which presumably destroys harmful protozoa with subsequent increase in the population of ammonia- and nitrate-producing bacteria. These ideas, however, were not substantiated by more recent studies. It appears that the increased growth of plants, observed in some instances after partial sterilization, is due to the release of nutrients, particularly nitrogen, from the exoskeletons of steam-killed organisms.

In treatment of nursery soils, sterilization by steam invariably presents considerable danger. If some portions of the soil escape sterilization, damping-off fungi may invade the entire area with increased intensity because their natural controlling agents have been eliminated.

FUNGICIDES

Sulfuric acid. The treatment of the seed-bearing surface soil layer with a solution of sulfuric acid is probably one of the oldest and most dependable methods of controlling damping-off disease. Because prolonged use of the acid has a definite deteriorating effect on soil fertility, such treatments should be restricted to cases of utmost necessity. But they cannot be entirely discarded in view of the questionable efficiency of other available means of disease control. If application of sulfuric acid is conducted correctly and is followed by readjustment of reaction and fertility of the soil, its adverse effects on nursery stock are much milder than those produced by many other fungicides. Both hydrogen and sulfate ions are far less toxic to plant tissues than are mercury or carbamate compounds.

To a great extent the deterioration of soil fertility under acid treatments resulted from application of strongly concentrated acid solutions. Such treatments were made in the belief that the acid could be diluted by irrigation water applied later on, an assumption contrary to the principle of exchange reactions. The injury to soil or seed caused by strong acid solutions cannot be alleviated by washing with water any more than can the injury to the acid-splashed face of a person.

As experience on noncalcareous sandy soils has shown, the best results are obtained by applications of a 1.2 to 1.5 per cent solution by volume at the rate of 5 gallons per 100 square feet. The use of stronger solutions involves danger of chemical injury of sprouting seedlings; the use of weak solutions, below 1 per cent, often leads to an increase in damping-off damages because such solutions fail to control parasitic fungi while they eliminate hyperparasites.

The solution is prepared in a barrel or another large nonmetal container by the addition of concentrated commercial acid to water, with constant stirring. Water must not be poured into the acid as the mixture may explode and cause dangerous acid burns. It is a good idea to keep handy a solution of ordinary baking soda (a tablespoonful per quart of water) to place on skin splashed by acid.

The solution is transferred from the barrel by means of a hose or spigot into watering cans and sprinkled uniformly on top of the seeded nursery beds. As soon as the acid has soaked into the soil the bed is thoroughly watered.

The acidity of the soil should be decreased by periodic watering so that the reaction approaches pH 5.0 at the time of germination. The speed with which the acidity decreases depends upon the mineralogical composition and colloidal content of the treated soil. The affinity of some soils for acid is so great that watering will not raise the reaction to a value higher than pH 3.0 before the seedlings germinate, and the plants may suffer from chemical injury or malnutrition. Other soils have such a small affinity toward acid, or such a high neutralizing capacity, that watering will nullify the effect of acidification, thus making possible the reinvasion of the surface soil by parasites from the deeper untreated layers. Sulfuric acid treatments are totally ineffective on soils of alkaline reaction high in carbonates because even a highly concentrated acid solution is instantly neutralized by the calcareous material. On all such soils the use of sulfuric acid is impractical and some other method of control should be employed (Wilde, 1937).

Soil fertility decreased by acid treatment should be reestablished by liquid fertilizers applied six weeks after germination or in the spring of the next growing season. To reduce the adverse effects of sulfuric acid, the treated beds should be devoted to transplants after seedlings reach plantable size and are lifted; in this way the acid will not have to be applied to the soil for three or even four years. This is a practice which it is advisable to follow in regard to all fungicide treatments. The alternation of seedlings and transplants also provides a chance to correct soil acidity as well as content of nutrients by application of lime, organic remains, and fertilizers.

Formaldehyde. Formaldehyde treatments are likely to be best adapted for use on soils of fine texture and on soils high in carbonates. The use of formaldehyde has also been recommended on strongly acid soils to prevent further increase in hydrogen ions, which is unavoidable in treatments with sulfuric acid (Baxter, 1952). The concentration of the formaldehyde solution varies from 1:100 to 4:100 of 37 per cent commercial formalin. The concentration most commonly used is 2:100.

The solution is applied at the rate of about 5 gallons per 50 square feet at least one week ahead of seeding. Under unfavorable conditions a longer period may be needed for evaporation of the formaldehyde. It is important that the soil disinfected with formaldehyde be disturbed as little as possible at the time of seeding, and especially should not be contaminated by applications of untreated soil as a top dressing.

The greatest drawback to the use of formaldehyde is the difficulty in establishing the length of time which must elapse between treatment and seeding. Too short a period results in chemical injury of seedlings, whereas too long a period may decrease the effectiveness of formaldehyde and result in more severe damping-off than on untreated areas. Another unfavorable effect of formaldehyde treatment is the deterioration of soil structure from heavy drenching with the solution (de Ong, 1953).

In studies conducted at the Rothamsted Experiment Station, soil treatment with heavy applications of formaldehyde produced marked increases in the growth of seedlings. This effect undoubtedly results from the elimination of competition of microbes, as well as from the additional nitrogen released from the tissues of eradicated organisms. This is an effect essentially similar to that achieved by partial sterilization. Unless special precautions are taken toward reinoculating the soil with beneficial organisms and reestablishing soil fertility, treatments of this type eventually will ruin the soil fertility and lead to production of planting stock of inferior quality.

The use of paraformaldehyde in dust form has been suggested but needs a thorough trial in forest nurseries before it can be recommended.

Sulfur powder. Sulfur powder has been applied extensively in forest nurseries as a means of damping-off control but has not always proven to be efficient. Nevertheless, sulfur in moderate quantity is desirable on all nursery soils which are less acid than pH 6.0. Sulfur acts as a preventive against some damping-off fungi by acidifying the soil and often serves as a fertilizer. The usual rate of application varies from 100 to 300 pounds per acre, depending upon the reaction and texture of the soil. Even this light application must be made well ahead of seeding, as the intermediate products formed in sulfur oxidation are extremely toxic to plants. A thorough incorporation of sulfur powder throughout the surface 8-inch layer of soil is essential.

An addition of sulfur may be advantageously supplemented by a generous application of litter, which will speed up the oxidation process. The sulfur most commonly used in forest nurseries is the grade of which 90 per cent will pass through an 80-mesh sieve.

Aluminum sulfate. This salt has been used extensively for acidification of soil and damping-off control (Hartley, 1929). It has proved to be only partly efficient as a fungicide. The repeated application of aluminum sulfate at the biennial rate of 400 pounds per acre on poorly buffered sandy soil led to deterioration of the stock, largely because of conversion of available phosphorus into insoluble aluminum phosphate. However, to obtain deep acidification of alkaline nursery soils in the prairie region, as much as 1000 pounds per acre of aluminum sulfate was applied without noticeable ill effects. The amount necessary for acidification of a particular soil is usually found by treating small samples with different quantities of aluminum sulfate and measuring the resulting pH values.

Mercury compounds. Corrosive sublimate (mercuric chloride) and calomel (mercurous chloride) have been applied singly, together, and in combination with many other compounds. The use of mercurial fungicides in forest nurseries, however, has been only on a limited scale, partly because of the high cost of the chemicals and the danger involved in handling these lethal substances. Moreover, the damage to nursery stock caused by the extreme toxicity of the mercury ion at times outweighed the benefit achieved by the control of parasitic organisms. Even 30 pounds per acre of calomel in a 1:2000 dilution presents definite possibility of direct injury to sprouting seedlings and to beneficial soil organisms. By and large, the mercury compounds are being replaced in nursery practice by other fungicides which exert a milder deteriorating effect on seedlings and which undergo in the soil a more rapid decomposition.

Thiram. Tetramethyl thiuram disulfide is also known under the trade names **Thiosan** and **Arasan** and is used largely as a seed disinfectant. The seed is pelleted with 50 per cent arasan, using 4 per cent methyl cellulose as a binder. This treatment has been found effective in controlling both pre-emergence and post-emergence damping-off. Normal dosage is 4 to 8 ounces of arasan per pound of seed (Berbee *et al.*, 1953).

A modification of thiram, called tersan, contains a wetting agent and is used for direct application to the soil. It is applied as an emergency measure, to control damping-off after the seedlings have sprouted. The usual application is 50 pounds of tersan per acre, distributed in an emulsion at the rate of at least 6 gallons per 100 square feet.

Miscellaneous means of fungus control. Glacial acetic acid, pyroligneous acid, phosphoric acid, nitric acid, zinc salts, various copper compounds, ferbam, ziram, other dithiocarbamates, and numerous other chemicals have been suggested for the control of soil-inhabiting parasitic fungi. The use of these compounds in forest nurseries has been limited because of their high cost, inefficiency, or deteriorating effect on the soil fertility. Treatment of seedbeds with boiling water and addition of charcoal have been tried, but the results were not satisfactory. The covering of seedbeds with pure sand previous to seeding gave satisfactory results in some instances.

Some foresters avoid disinfecting the soil by abandoning the nursery and selecting a new site as soon as parasites become troublesome. This practice, however, may not always be satisfactory, unless the new nursery is located on recently cleared land. Quite often soils which have been cleared for some time, including those of acid reaction, are infested with parasites.

Use of organic remains. A number of observations in the greenhouse and in several nurseries has indicated that the addition of acid peat and raw humus has a tendency to reduce fungus diseases. This effect may be attributed to a variety of conditions, such as increase in soil acidity, buffering action preventing injury to roots by salts in solution, and supply of nutrient humates which may increase the strength of root tissues of emerging seedlings and thus shorten the period of their susceptibility to disease (Wilde and Hull, 1937; Ten Houten, 1939). In a systematic greenhouse study of sandy soils infested with *Pythium irregulare* and *Rhizoctonia solani,* the addition of various biologically active organic remains at the rate of 3.2 per cent by volume reduced the incidence of damping-off disease about 50 per cent (Mikola, 1952). These results were achieved with practically no change in soil reaction and were attributed by the investigator to release of readily available nutrients from the humus. Thus the designation of damping-off disease by German practitioners as "Bodenmüdigkeit" or "soil tiredness" may be entirely justified. It is possible that the application of suitable organic remains increases the number of organisms directly or indirectly responsible for the reduction of parasites (Waksman, 1952).

INSECTICIDES

Insecticides are intended to exterminate parasitic insects as well as other members of the *Arthropod* phylum. These compounds kill by mere contact, by stomach poisoning, or by asphyxiation. Accordingly, insecticides are rated as **contact poisons, stomach poisons,** and **fumigants.** Quite often, however, these compounds exert all three effects simultaneously.

Lead arsenate. Lead arsenate is one of the oldest insecticides and has been used for many years for treatment of soils infested with parasitic insects. Its efficiency is questionable, since cases have been reported in which the seedbeds were destroyed by white grubs in spite of heavy applications of the insecticide. In a quantity exceeding 200 pounds per acre, lead arsenate produces an adverse effect on soil fertility and is directly toxic to seedlings, especially in strongly acid soil (Fig. 13–3). It causes either death of the young plants or serious injury to the roots, which later become subject to the attack of *Fusarium* and other fungi.

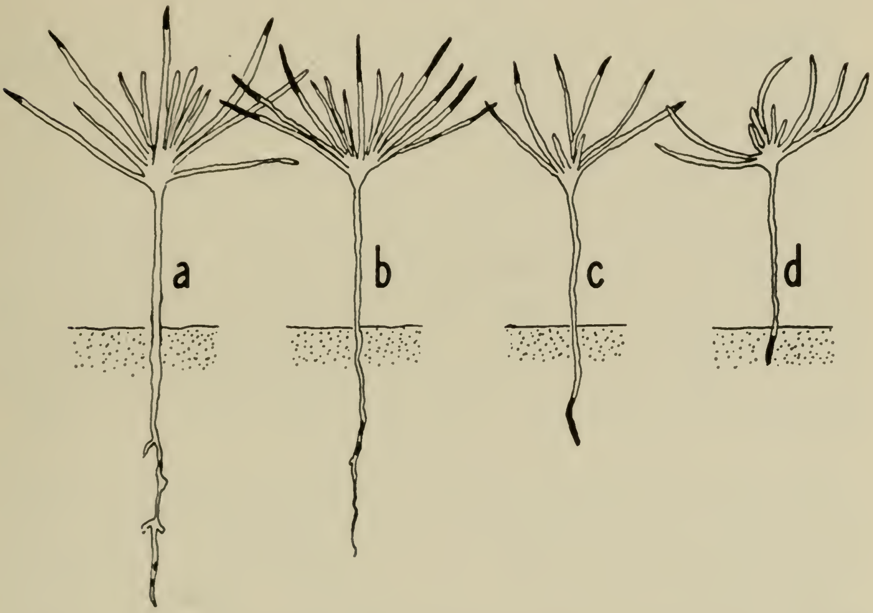


Fig. 13–3. Injury of sprouting pine seedlings by lead arsenate applied to unbuffered strongly acid sandy soil at the following rates: (*a*) 50 pounds per acre; (*b*) 100 pounds per acre; (*c*) 200 pounds per acre; (*d*) 400 pounds per acre. Note the regularity in the degree of root burning and plasmolysis of foliage.

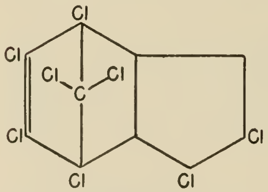
Arsenic gives the same color reaction as phosphorus in the presence of molybdate reagent. Consequently, in analyzing soils treated with lead arsenate, erroneously high quantities of phosphorus may be recorded.

Carbon disulfide emulsion. Carbon disulfide has been used in the past for the control of animal parasites and insects, either alone or in combination with formaldehyde to obtain simultaneous control of damping-off fungi. The composition of the emulsion and its rate of application vary with conditions, and satisfactory disinfection requires the supervision of an expert (Fleming and Baker, 1935). Pure carbon disulfide is highly inflammable and explosive. Prolonged exposure to the gas causes dizziness. The cost of treatment is very high. Carbon disulfide does not satisfactorily control white grubs, which are the most destructive pests in forest nurseries. These shortcomings make the use of carbon disulfide in forest nurseries highly questionable. This is especially true because of the availability of recently discovered superior insecticides.

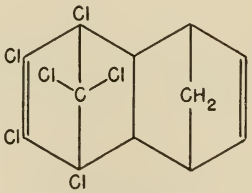
Chlor-picrin. A heavy liquid made by the interaction of bleaching powder and picric acid (Howard and Stark, 1939), this insecticide destroys nematodes and insect parasites. In treating nursery beds, holes are made 5 to 6 inches deep and 14 inches apart. Approximately 2.5 ml. of liquid is injected into the hole by means of a special pipette. The hole is immediately closed by pinching the soil together with a thrust of the heel. The entire bed is then covered with oil-treated paper, which is tucked down at the edges of the bed to a depth of 3 to 4 inches. After three days the paper is removed and the bed prepared for seeding. Treatment is extremely dangerous to growing nursery stock, as well as to the person performing the application. This insecticide should be used only under expert supervision and in cases of utmost necessity.

Benzene hexachloride. Technical benzene hexachloride contains five isomers, of which the gamma isomer is the most effective. The commercial product, Lindane, is practically pure gamma isomer and is incomparably more toxic than the unpurified compound. As little as one pound per acre of the gamma isomer is sufficient to produce effective control of large white grubs. However, benzene hexachloride and its trichlorobenzene breakdown products have highly toxic effects on mycorrhizae and other beneficial soil organisms. This makes the use of benzene hexachloride in all forms undesirable in nursery soils (Simkover and Shenefelt, 1952).

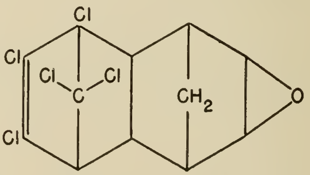
Chlorinated hydrocarbons. Chlordane, heptachlor, aldrin, and dieldrin, related to DDT, are very complicated structurally, as shown below.



Chlordane



Aldrin



Dieldrin

Chlordane, or octachloro-methano-tetrahydroindane, is marketed either as a concentrated emulsion or as a wettable powder of 40 to 50 per cent concentration. It is applied either as a dust or emulsion and kills parasites, such as white grubs and root weevils, by contact or as a stomach poison. The common rate of application is 10 pounds of the actual chlordane per acre. At this concentration, chlordane serves more or less as a preventive measure rather than as a drastic exterminator. It eliminates insects largely in the early stages of their growth and thereby precludes the building of large populations, particularly that of white grubs. Chlordane is a stable compound, and over a long period a residue may accumulate in the soil in a toxic concentration (de Ong, 1956). However, single applications of chlordane as high as 100 pounds per acre did not produce noticeable deterioration of red pine seedlings (Simkover and Shenefelt, 1952).

Heptachlor is a complex chlorinated hydrocarbon similar to chlordane but of somewhat higher efficiency. It finds constantly increased use, often replacing chlordane. It is known also as Velsicol 104 and is sold as a 2 per cent dust, emulsion, or oil solution. Dosages as low as 1 pound per acre have been found to control white grubs.

Aldrin, hexachlorohexahdro-*endo, exo*-dimethanonaphthalene (HHDN), is an insecticide of general utility, acting as a contact poison, stomach poison, and to a limited extent as a fumigant. It is sold as a wettable powder, dust concentrate, low percentage dust, and as a 60 per cent solution. The usual rate of application is 2 to 4 pounds of the pure aldrin per acre. Soil applications should be worked in to a depth of 4 to 6 inches. No injury to plants has been reported from treatments as high as 10 pounds per acre.

Aldrin is one of the few insecticides that has found use in soils of forest plantations. In some cases, a spray of roots with a 1 per cent emulsion of aldrin at the time of planting increased survival of trees from 26 per cent on untreated areas to 98 per cent on treated plots (Shenefelt, 1956).

Dieldrin, hexachloroepoxyoctahydro-*endo, exo*-dimethanonaphthalene (HEOD), is closely related to aldrin; according to E. Lichtenstein (1956, personal communication), dieldrin is formed in soil by oxidation of aldrin. The rate of application for soil treatments is similar to that of aldrin.

HERBICIDES AND ARBORICIDES

2,4-D, or 2,4-dichlorophenoxyacetic acid, is a herbicide of a hormone type. It produces an excessive stimulation of growth of herbaceous and broad-leaved plants, leading to their death. The action is slow, and it may take more than a month to kill both tops and roots. The 2,4-D is usually applied directly to foliage as a spray, the rate of application varying from 0.1 to 10 pounds of the pure compound per acre, depending on the eradicated vegetation and conditions of climate. If the herbicide is applied directly to the soil, the residue may be injurious to emerging seedlings for a period of from two weeks to several months. Fine-textured soils retain residues longer than do sandy soils. Abundant rainfall or artificial irrigation promotes the leaching of the toxic substances.

2,4,5-T, or 2,4,5-trichlorophenoxy acetic acid is a hormone type herbicide similar to 2,4-D. It is used principally on plants resistant to the latter compound.

Stoddard solvent, a refined petroleum fraction, is used to control annual weeds. It also finds application as a pre-emergence spray for slowly sprouting seedlings. The common rate of application is 50 to 100 gallons per acre.

Allyl alcohol, $CH_2 \cdot CH \cdot CH_2OH$, is used for weed control. It is usually applied at the rate of 50 gallons per acre. Occasionally, allyl alcohol exerts a strong stimulation effect on the growth of nursery stock.

Ammonium sulfamate, or ammate, is used for eradication of shrubs and unwanted trees. It kills trees faster that girdling, and inhibits sprouting. The compound is not toxic to human beings, livestock, and wildlife (Baxter, 1952).

EFFECT OF BIOCIDES ON THE AVAILABILITY OF NUTRIENTS, MICROBIOLOGICAL ACTIVITY OF SOIL, AND PROPERTIES OF NURSERY STOCK

To prevent the negative results, the use of biocides must be paralleled by careful observations of their immediate and residual effects on the availability of nutrients, behavior of beneficial soil organisms, and external as well as internal development of nursery stock.

The effect of biocides in decreasing the availability of nutrients was strikingly illustrated by the report of Voigt (1955), who used foliar analysis to detect the changes in soil fertility. Some of his data are given in Table 13–1. The drastic decrease in the uptake of different nutrient elements, observed by Voigt, was a consequence of the high rate of application of the biocides. The use of such heavy applications in experimental work is justified by two reasons: under conditions of actual soil management, uneven distribution of the chemicals leads to their very high local concentration; repeated applications of biocides often produces an accumulation of residues in a narrow zone of enrichment where the chemicals attain a concentration by far exceeding that of a single application.

TABLE 13–1

Average Nutrient Content of Crowns of One-Year-Old Monterey Pine Seedlings Raised in the Greenhouse on Soils Treated with Different Biocides (After Voigt, 1955)

Treatment—rate per acre	Average content of nutrients per seedling				
	Nitrogen (mg.)	Phosphorus (mg.)	Potassium (mg.)	Calcium (mg.)	Magnesium (mg.)
Check	2.72	0.45	1.67	0.63	0.33
Aluminum sulfate, 1000 lb.	1.80	0.19	1.29	0.29	0.21
Calomel, 80 lb.	1.83	0.39	1.06	0.37	0.20
Thiosan, 290 lb.	1.79	0.10	0.91	0.28	0.19
Benzene hexachloride, 5 lb. (gamma isomer)	1.76	0.28	1.00	0.19	0.28

Another investigation by Voigt (1954), employing P^{32}, revealed that the addition of aluminum sulfate, thiosan, or benzene hexachloride appreciably inhibits the absorption of phosphorus.

The observations by Persidsky and Wilde (1955) of the influence of different eradicants on microbiological characteristics of the soil are summarized in Table 13–2. These results indicate that addition

TABLE 13–2

Effect of Various Biocides on Microbiological Characteristics of Soils (After Persidsky and Wilde, 1955)

Eradicants applied and rate of application per acre	Number of colonies per molecular filter	Cellulolytic activity (%)	Proteolytic activity (%)	Nitrification capacity (ppm.)	Evolution of CO_2 (mg./g.)	Weight of *A. niger* mycelia (g.)	Growth of excised roots of lupine (mm.)
Untreated soil	518	65.3	72.4	7.0	168.3	1.386	7.5
Chlordane, 10 lb.	334	45.4	42.8	1.1	141.9	1.130	5.1
Allyl Alcohol, 50 gal.	253	29.3	45.7	3.5	58.3	0.696	3.0
Stoddard oil, 100 gal.	221	33.3	38.1	0.8	34.1	0.928	4.2
Thiosan, 120 lb.	138	28.1	42.8	2.9	52.8	0.829	2.0
Aluminum sulfate, 500 lb.	51	46.7	44.7	1.7	23.1	0.831	4.3
Formalin, 5000 gal.	63	22.7	33.3	2.7	37.4	0.942	1.6
Calomel, 40 lb.	48	37.3	38.1	0.6	72.6	0.705	1.5
Benzene hexachloride, 1 lb. (gamma isomer)	38	32.0	47.6	1.3	25.3	0.802	2.6

of most biocides, even at a normal rate of application, decreases the number and growth of microorganisms, cellulolytic and proteolytic activity, nitrification capacity, and evolution of carbon dioxide. Certain biocides arrest the growth of live roots through the emanation of toxic volatile substances.

A deleterious effect of equal importance is exerted by biocides on mycorrhizal fungi and nodule bacteria, the symbiotic organisms assisting in the nutrition of seedlings. At high concentrations, calomel, thiosan, and benzene hexachloride cause either partial destruction of cortical cells of embryonic short roots or a complete castration of the mycotrophic organs. Under conditions of less severe toxicity short roots show restricted or arrested penetration of mycelia and reduced development of the Hartig net (Fig. 13–4). At times in the presence of biocides, mycotrophic organs exhibit greatly modified morphology resembling endocrinological abnormalities (Wilde and Persidsky, 1956). Some of these modifications are characteristic for certain specific biocides, as illustrated in Figure 13–5.

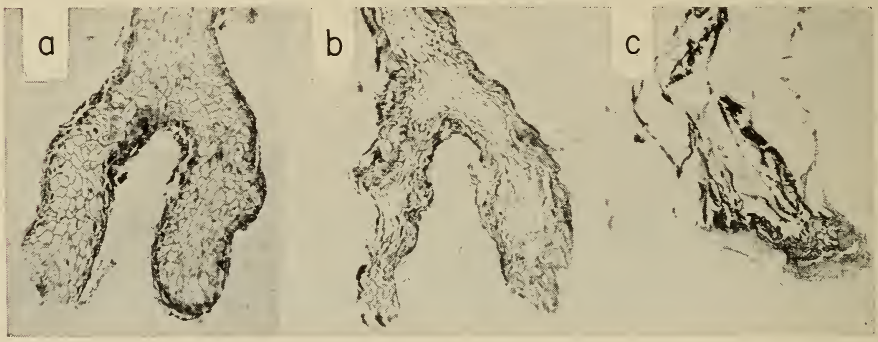


Fig. 13–4. Alterations of mycorrhizal short roots of *Pinus radiata* under the influence of eradicants: (*a*) normal bifurcate short root with a well-developed Hartig net; (*b*) bifurcate short root with a reduced intercellular penetration of mycelia under the influence of thiosan, applied at the rate of 125 pounds per acre; Hartig net is largely replaced by stele tissue; (*c*) simple mycorrhizal short root produced under the influence of calomel, applied at the rate of 40 pounds per acre; disruption of the mantle and disintegration of cortical cells.

According to Wallis (1957), applications of chlordane, thiosan, and allyl alcohol at high rates reduce the number of *Rhizobium* bacteria, colonizing the individual nodules, but do not suppress entirely the formation of nodules.

Very fortunately, in most instances applications of biocides fail to sterilize the entire root-bearing region or root systems. In consequence, the organisms escaping destruction in time reinvade the rhizosphere and reestablish the normal nutrition of plants. This is

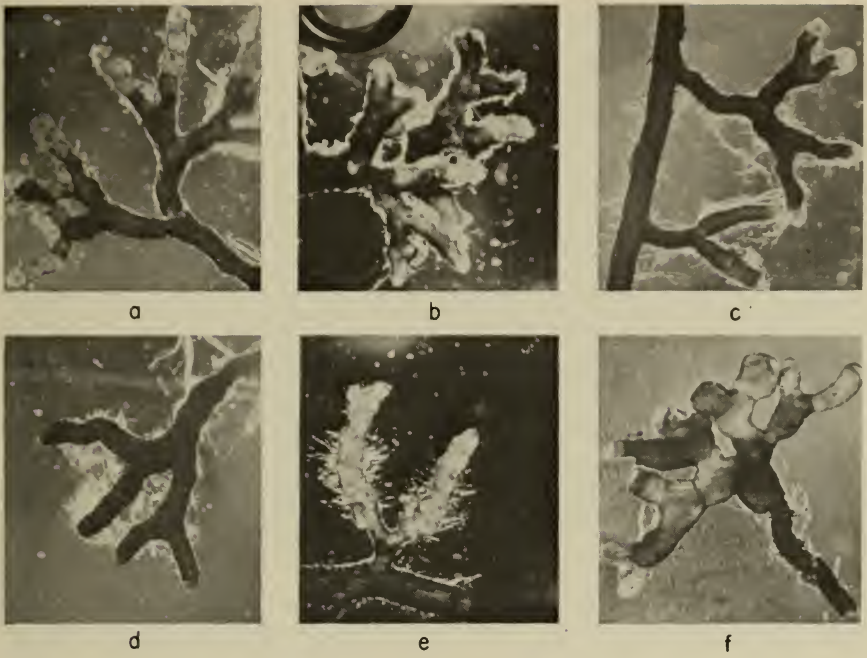


FIG. 13-5. Development of ectotrophic mycorrhizae of *Pinus radiata* under the influence of various biocides applied to the soil at moderate rates: (*a*) check, untreated sandy soil—normal bifurcate rosary-like mycorrhizal short roots; (*b*) Stoddard solvent, 50 gallons per acre—mycorrhizal clusters of coralloid pattern; (*c*) thiosan, 62 pounds per acre—non-rosary forked short roots; (*d*) chlordane, 5 pounds per acre—nearly normal non-rosary forked short roots; (*e*) benzene hexachloride, 0.5 pounds per acre—clovate or clublike sessile mycorrhizae; (*f*) calomel, 20 pounds per acre—blunt, forked short roots of a lobate pattern.

especially true of mycorrhizal fungi, which appear to possess a great survival potential.

As a general rule, the presence of biocides in high concentrations exerts a depressing effect upon the growth of seedlings. However, this rule is not without notable exceptions (Persidsky and Wilde, 1955). Quite often biocides stimulate the growth of tops, roots, or entire seedlings, as illustrated by Table 13–3 and Figure 13–6. Considering the quality of planting stock, this stimulation may be either beneficial or harmful.

An extreme example of definitely harmful stimulation of *Pinus radiata* by allyl alcohol was observed by Wilde *et al* (1956). Allyl alcohol, a pungent liquid constituent of garlic and mustard, provoked in transplanted seedlings elephantine development, together with a high degree of succulence and vulnerability to drought (Fig. 13–7).

There is little need for further illustrations of the pitfalls encoun-

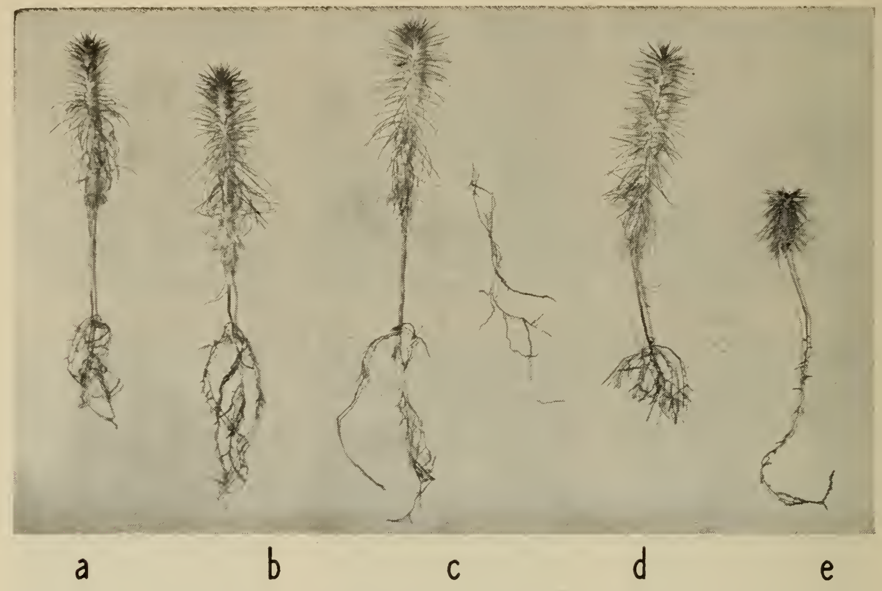


Fig. 13-6. Growth of 1-0 *Pinus radiata* seedlings in a coarse sandy soil treated with different biocides at the indicated rate of application: (*a*) untreated soil; (*b*) chlordane, 10 pounds per acre; (*c*) allyl alcohol, 50 gallons per acre; (*d*) benzene hexachloride (gamma isomer), 1.0 pounds per acre; (*e*) calomel, 40 pounds per acre.

TABLE 13-3

Effect of Eradicants on the Growth of One-Year-Old Seedlings of Montery Pine, *Pinus radiata,* Raised in Sand Cultures. Oven-Dry Weights of Average Seedlings

Eradicant applied and rate of application per acre	Seedling "in toto" (g.)	Top (g.)	Root (g.)	Top-root ratio
Untreated soil	0.177	0.143	0.034	4.2
Chlordane, 10 lb.	0.172	0.132	0.040	3.3
Allyl alcohol, 50 gal.	0.191	0.143	0.048	2.9
Stoddard oil, 100 gal.	0.180	0.108	0.072	1.5
Thiosan, 120 lb.	0.146	0.114	0.032	3.6
Aluminum sulfate, 500 lb.	0.130	0.087	0.043	2.1
Formaldehyde (0.7%) 5000 gal.	0.140	0.089	0.056	1.5
Calomel, 40 lb.	0.107	0.098	0.009	10.8
Benzene hexachloride, 1 lb. (gamma isomer)	0.176	0.130	0.046	2.8

tered in the use of lethal chemicals. It is obvious that only with utmost precautions is it possible to exterminate parasitic fungi, harmful insects, and noxious weeds, and yet raise in the same soil vigorous seedlings destined to form the future forests.

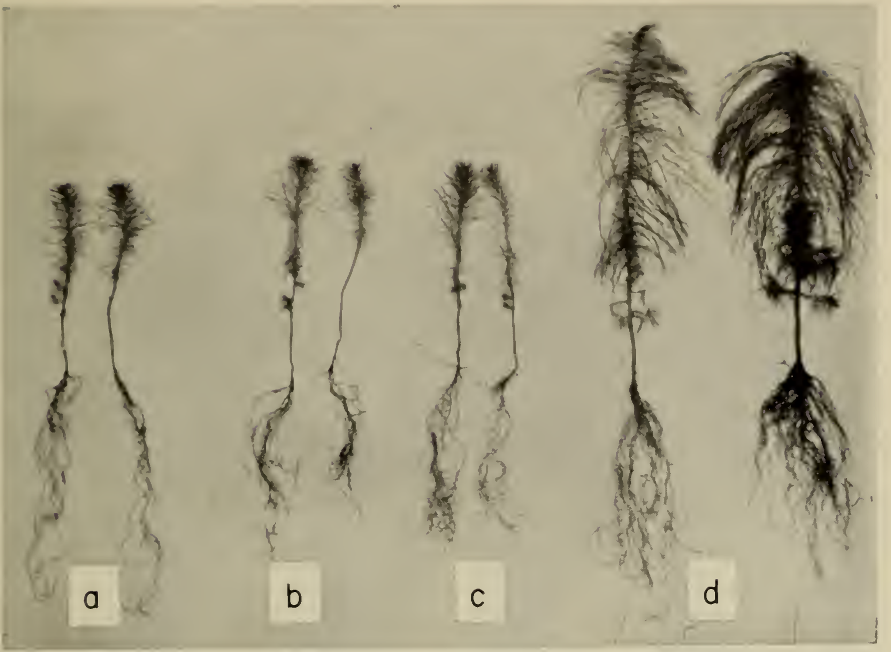


FIG. 13–7. The growth of 8-month-old Monterey pine seedlings in Carrington prairie silt loam. Prior to transplanting, the seedlings were raised in sandy soil either (*a*) untreated or treated as follows: (*b*) thiosan, 120 pounds per acre; (*c*) chlordane, 10 pounds per acre; (*d*) allyl alcohol, 50 gallons per acre. The drought-resistance test indicated that the overdeveloped stock from allyl alcohol cultures is highly vulnerable to drought.

On the other hand, it is clear at this time that economics have firmly imposed the use of chemical and biochemical compounds on nearly all phases of silvicultural work: production of nursery stock, maintenance of fire lanes, tree planting, partial cuttings, and protection of forest stands. Foresters engaged in these activities are already or soon will be "married" by the benzene ring to the array of chemicals, for better or for worse. Consequently, one of the most acute problems that faces foresters and soil specialists of today is to learn the ways and means by which the toxic residues of biocides may be either eliminated from the soil or rendered harmless to nursery seedlings and field planted stock.

There are but a few means now at the disposal of a forester to counteract the adverse influences of eradicants. One of them is the readjustment of soil fertility by the use of commercial fertilizers. However, such treatments must be conducted with utmost care and expert knowledge, for in many instances the addition of fertilizer salts immensely amplifies the deleterious effect of biocides. A more promising, though more expensive, method of soil renovation is the application of partly decomposed forest litter, activated composts, or liquid humates. As shown by Mader (1956) the addition of forest humus can restore the growth and vigor of stock on soils subjected to even drastic biocide treatments (Fig. 13–8). This regenerating effect is directly related to the content of applied biologically active organic remains. With heavy applications of biocides, the restoration of soil fertility may require as much as 25 cubic yards per acre of arthropod fine mull, duff mull, bran mor, and related ectorganic types of forest humus. However, even applications of liquid humates, delivering only a very small amount of organic matter, proved to be beneficial.

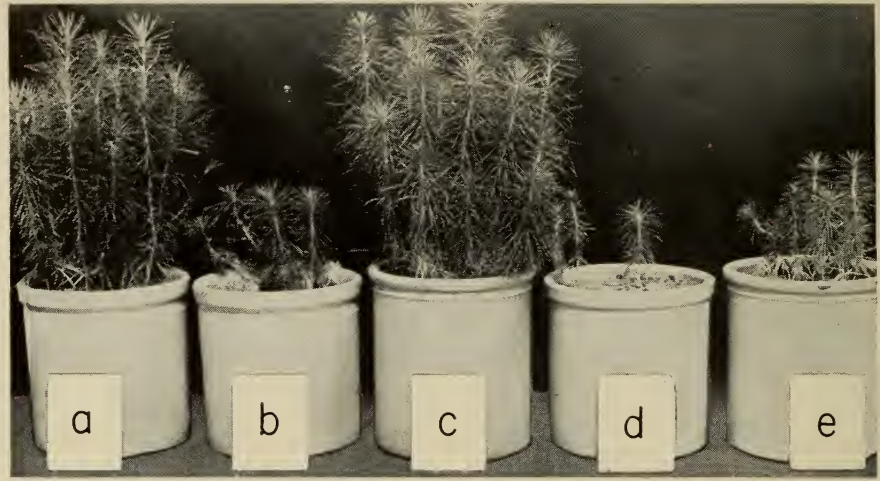


Fig. 13–8. Ameliorating effect of arthropod fine mull humus on the growth of Monterey pine raised in soils treated as follows: (*a*) fertilizer salts delivering 50 pounds of N, 250 pounds of K_2O, and 80 pounds of P_2O_5 per acre; (*b*) fertilizers plus 200 gallons allyl alcohol, 200 pounds thiosan, and 5 pounds gamma isomer benzene hexachloride on a per acre basis; (*c*) same treatment as *b* plus humus at the rate of 25 cubic yards per acre; (*d*) fertilizers plus 200 gallons Stoddard oil, 80 pounds calomel, and 300 pounds chlordane on a per acre basis; (*e*) same as *d* plus humus at the rate of 25 cubic yards per acre. The extent of the beneficial effect of humus can be fully appreciated only after considering the drastic, practically lethal treatment of the soil with both fertilizers and biocides. (After Mader, 1956.)

PREVENTIVE MEASURES

The spectacular effect exerted by biologically active organic remains on soil fertility and plant growth suggests the correctness of the old belief of Claude Bernard and some other biologists. The credo of this group of scientists is that the disease itself or its degree of virulence is often a direct function of the environment and the condition of the infested organism. Numerous examples from modern practice strongly suggest that the success of the forester's fight against nursery pests may lie less in the search for more efficient means of soil disinfection than in the proper adjustment of ecological conditions, biological relationships, and balanced nutrition. The latter is especially important because it hastens the early growth of plants and shortens the period of susceptibility of young stock to parasites.

In the light of these ideas, preventive measures acquire a particular significance. The saying that "an ounce of prevention is worth a pound of cure" may be literally applicable to forest nursery practice. The most important measures preventing the development of parasites may be briefly summarized as follows:

1. Very careful use of materials which encourage the development of parasitic fungi, e.g., alkaline organic remains, lime, wood ashes, and commercial fertilizers decreasing the acidity of the soil, such as sodium nitrate and calcium cyanamide
2. Maintenance of an acid reaction of nursery soil by applications of suitable acidifying agents, especially acid peat
3. Periodic analyses of nursery soil and maintenance of an adequate and balanced supply of available nutrients
4. Regular additions of suitable forest litter or ectohumus in order to assure an abundance of useful organisms as well as a supply of available nutrients for their sustenance
5. Restriction in the use of unbuffered fertilizers or any other unbuffered soluble salts
6. Maintenance of an adequate supply of soil moisture and an adequate degree of soil aeration by carefully regulated artificial watering
7. Protection of seedlings from extremes of climate by shading, windbreaks, mulching, watering, and other means
8. Rotation, careful use of green manure crops, sparse seeding, and when possible, fall seeding
9. Periodic examination of nursery stock and nursery soil, efficient control of parasites as soon as they appear, weed control, and other forms of sanitation

14

Without a floristic survey—no soil investigations; and vice-versa without a soil survey—no floristic investigations. SUUM CUIQUE.
—Arthur von Kruedener

Forest soil survey

Purpose of forest soil survey. In order to secure satisfactory growth of crops, the farmer improves the tilth of the soil by cultivation, rearranges the lay of the land by terracing, modifies drainage by the use of tile or the digging of ditches, and regulates fertility by application of lime, manure, and fertilizers. Such improvements are seldom practicable in silviculture, and the maximum income from a forest enterprise is usually attained by planting or by encouraging the tree species which are best adapted to a given set of site factors. The necessary information on site factors—climate, topography, ground water, and soil—is secured by means of a special study and mapping program called "forest soil survey." Because this survey usually deals with a whole complex of ecological conditions as well as the soil, it is also appropriately referred to as "forest land survey."

The survey of forest land constitutes the first and probably the most important step in the organization of a forest tract for planned management. It delineates the soils suitable for planting different tree species or for cutting forest stands by different methods. It forms the basis for the construction of yield tables, calculation of the annual cut, the determination of the expected financial return, and the appraisal of land for sale, exchange, and taxation. In many instances the survey greatly facilitates the solution of problems related to transportation, logging operations, and fire control.

Until recent years the survey of soils for forestry purposes was almost exclusively conducted by governmental agencies. With the acquisition of tax-delinquent lands by timber and paper industries, the survey of forest soils received a new and vigorous impetus. Leaders of private concerns had found it impossible to deal with an economic problem which involves an unknown value—the soil. Few of them could or would invest capital for tree-planting, thinnings, or improvement cuttings in an uncharted *terra incognita*, land of an undetermined productive potential. Moreover, business men were not blind to the sad fate of misoriented silvicultural efforts, examples of which are not lacking. A pine plantation yielding a half dozen cords of pulpwood at the age of forty years spells a 70 per cent loss on the investment. Equally high losses may be encountered in improvement cuttings of exacting hardwoods on sites where the trees are doomed to premature death by an inadequate supply of nutrients or by unsatisfactory physical conditions of the soil (Wilde, 1954). Hence, there is little doubt that in the future, survey of forest lands will provide bread and butter to many foresters, particularly those who managed to acquire knowledge of the environmental alphabet. The detailed account of soil surveying given in this chapter was instigated by the present state of forestry practice as well as its future prospects.

Technique of surveying. In surveying land the area is traversed back and forth at fixed intervals which vary from one-half to one-eighth of a mile, depending upon the nature of the land and the intensity of forest management. The distance is measured by careful pacing, while the direction is kept by means of a hand compass. Variations in soil and other conditions are recorded on the field map. In order to locate exact site boundaries, offsets are taken from the traverse line. Offsets are particularly important in hilly areas or tracts with dense forest growth. The details of mapping techniques are discussed by the United States Soil Survey Staff (1951). In recent years the difficult task of soil-surveying was facilitated by progress in aerial photography and the increased availability of accurate base maps.

The survey of forest lands is usually influenced by the rule of "practical balance," which requires the separation of small areas characterized by great differences and large areas characterized by small differences. According to this rule, in a region of coarse sandy soils frost pockets two acres or less in size should be mapped separately, whereas areas of light sandy loams can be overlooked unless they attain a size of five or more acres. The mapping of small but conspicuous areas, such as leatherleaf bogs, potholes, boulder pavements, and rock outcrops, is often desirable because of their value as landmarks.

Use of reports and maps of previous surveys. During the past fifty years, state and federal agencies have conducted numerous soil surveys (U.S.D.A., 1938). The results of these surveys, published as bulletins and maps, are of great assistance in the solution of forest management problems (Kittredge, 1928; Veatch, 1932; Donahue, 1936). This is particularly true of recent soil maps and survey reports which interpret soil features on a broad scientific basis. The older maps, however, may also be converted into maps useful for reforestation and forest management with some additional field work. This conversion may require either consolidation or further subdivision of the types originally surveyed (Sampson, 1930; Hough, 1942).

The classifications of the early soil surveys were based largely upon the possibilities of agricultural land utilization, an approach which is often in discord with the interests of forest management. Frequently the conditions of forest growth are essentially the same on a number of soil types of different agricultural value, for example, stony or stone-free soils and loam or silt-loam soils. On the other hand, soil types of agricultural classifications may not be sufficiently uniform to satisfy the needs of forestry practice. This is especially applicable to soils of minor agricultural value, such as coarse sandy soils of glacial outwash, soils of rough morainic deposits, and poorly drained soils (Wilde, 1932).

In surveying land for agricultural use, the topography was usually classified into different types: level, undulating, rolling, or rough (Whitson, 1927). The composition of the soil profile varies, however, depending upon its location on top of a hill, on a slope, or in a depression. Therefore, surveys which consider only the general lay of the land neglect essential differences in the type of organic matter, degree of leaching, content of nutrients, and other important soil features. This is particularly true in the glaciated regions of the north, where soils of terminal moraines were mapped in reconnaissance surveys as a single type, for example, "Kennan loam." The elevated portions of such deposits often support maple, basswood, and other hardwoods with base-enriched foliage. These hardwood stands usually maintain a nearly neutral reaction of the soil, its deep layer of mull humus, and its friable structure. On the other hand, the lower slopes of morainic ridges are occupied by stands with a predominance of acidophilous conifers, such as hemlock, balsam fir, and spruce. The acid litter of these species promotes an accumulation of raw humus and the development of strongly leached, cemented or compacted podzol soils. Since mull soils and podzols require essentially different methods of reforestation and selection cuttings, they must be carefully separated by additional survey.

Fig. 14–1 illustrates a more complex assortment of soil-forest units encountered in the hilly landscape of pitted outwash whose diversified soils appear on the old maps under the single name of "Vilas sandy loam."

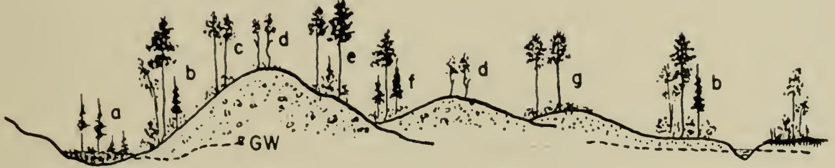


Fig. 14–1. Forest sites encountered on glacial sandy deposits derived from granitic rocks: (*a*) stagnant pothole—black spruce-tamarack of *Ledum-Chamaedaphne* type; (*b*) swamp-border podzol—pine-aspen-birch-balsam fir of *Cornus-Robus* type; (*c*) slightly podzolized denuded sand, steep southern exposure—jack pine-red pine of *Myrica-Gaultheria* type; (*d*) barren gravelly sandy ridge—jack pine of *Cladonia-Arctostaphylos* type; (*e*) podzolized sandy loam, northern exposure—red pine-white pine of *Vaccinium-Gaultheria* type; (*f*) sandy loam podzol with ortstein—white pine-balsam fir of *Vaccinium-Cornus* type; (*g*) melanized sand—red pine of *Arctostaphylos-Ceanothus* type.

Soils containing less than 15 per cent of silt and clay particles are of minor value for farming. Therefore, these soils appear in agricultural classifications as a single textural type, for instance, "Plainfield sand." From the standpoint of reforestation, however, small differences in the content of fine separates in sandy soils are of great importance. In northern regions, soils carrying less than 5 per cent of silt and clay are suitable only for planting pioneer species, particularly jack pine; slightly better soils are adapted to more exacting red pine; still heavier soils, containing more than 12 per cent of fine particles, may support white pine and other species of rather high moisture and nutrient requirements. Thus, the survey of sandy soils for forestry purposes requires an especially detailed textural classification.

On the other hand, the colloidal content of fine-textured soils ceases to be a limiting factor, and its knowledge is of minor significance to the forester. As far as texture is concerned, heavy soils are capable of supporting any tree species. Therefore, several textural types of agricultural classifications, such as loam, silt loam, and clay loam, may often be regarded as one soil type. Detailed classification of loam and clay soils is more meaningful if made on the basis of their structure, permeability, internal drainage, and aeration.

Some agricultural soil surveys differentiate the soil types according to the amount of stones per acre, since stoniness is a critical factor in agricultural land utilization. In such classifications some types may be divided into as many as four subtypes. From the standpoint of silviculture, however, it is sufficient to separate only the areas where stones preclude furrow planting or land scarification.

Degree of accuracy and cost of survey. The survey of land for forestry purposes is generally confined to specific areas selected for intensive forest management. It seldom covers an area larger than one township, or 36 square miles, and it is ordinarily accomplished by traversing land at intervals of one-eighth of a mile. The area mapped as a separate type may be as small as two acres.

A survey of this degree of intensity is relatively expensive, its cost usually running in the proximity of 20 cents per acre. Such an outlay is nevertheless warranted, because forest enterprise is a long-time investment which includes not only the cost of tree-planting and thinnings but also the expense on taxes, fire protection, and silvicultural care with compound interest on all this money for a period of many years. It is sufficient to point out that the initial cost of reforestation of one section, or 640 acres, at present day prices is nearly $15,000, and the total investment at the end of a rotation may reach $50,000. The cost of a detailed soil survey of one section is about $150, which constitutes 0.3 per cent of the total investment.

Equipment used in the survey of forest land. Before leaving for the forest, the chief of the surveying party should check equipment and apparatus needed for the survey. The failure to take some essential item may cause an aggravating and embarrassing delay of work. The following list includes the most important articles required for examination of soils, mensuration and floristic analyses, surveying, and preparation of maps:

Examination of soils: Spades, augers, sampling tubes, samplers for the determination of soil-volume weight, aluminum containers, folding rulers for profile measurements, notebooks, waterproof bags for soil samples, and equipment for rapid analyses of soil and ground water, especially that for the determination of reaction, texture, air permeability, content of carbonates, and specific conductance.

Mensuration and floristic analyses: Hypsometer, diameter-type, increment-borer, axe and saw, 100-foot steel surveyor's chain, standard forms for recording data on stand's growth and composition of ground cover, blotters and press for the collection of plants, manual for identification of plants.

Surveying and drafting equipment: Forester's compasses, tally counters, field sheets, graduated rulers, triangles, drawing and tracing paper, pencils, pens, erasers, ink, and thumbtacks. A plane table with accessories if there is no base map and if accurate survey of roads is required. An accurate tire-pressure gage if the speedometer of a car is used for measuring distances.

Establishing survey units. The greatest fault of early soil surveys was the establishment of soil types on the basis of speculative assumptions rather than on the basis of observations of soils and growth of plants in nature. As a result of this, in many instances "the soil surveyor knew the difference in soil properties when the vegetation did not." To overcome this discrepancy, the abstract classifications were gradually subjected to critical ecological analysis, using as an indicator the actual growth of forest stands. As a result mere "soil" classifications were replaced by broader "site" classifications (Kruedener, 1927; Vater, 1916; Cajander, 1949). This trend has found its expression on a large scale in soil-vegetation surveys of California (Gardner and Retzer, 1949; Wieslander and Storie, 1952).

The procedure for establishing silviculturally significant soil or land types comprises two separate steps: reconnaissance and sample plot study.

Reconnaissance. Preliminary measures are confined to court house, library, and drafting room and include assembling all pertinent information on the area to be surveyed, especially publications on geology, soil survey reports, and maps of recent date. Occasionally, a brief discussion with an experienced geologist, soil specialist, or forester on the university campus, at an experiment station, or other center, may save days of study. If possible, a reliable base map is prepared on a scale convenient for soil-mapping, preferably 8 inches to a mile (Fig. 14–2). Then two copies of individual sections are made by the offset process. One of these sets is used for transfer of boundaries of forest cover and other information which may facilitate field mapping; another set is kept in field headquarters and is used for an accurate daily transfer of soil boundaries from the field sheets.

Reconnaissance itself consists of a general examination of the area, made by the chief surveyor, usually in the company of the landowner or supervising forester. The main objective of this examination is to learn the entire gamut of soil and ecological conditions of the

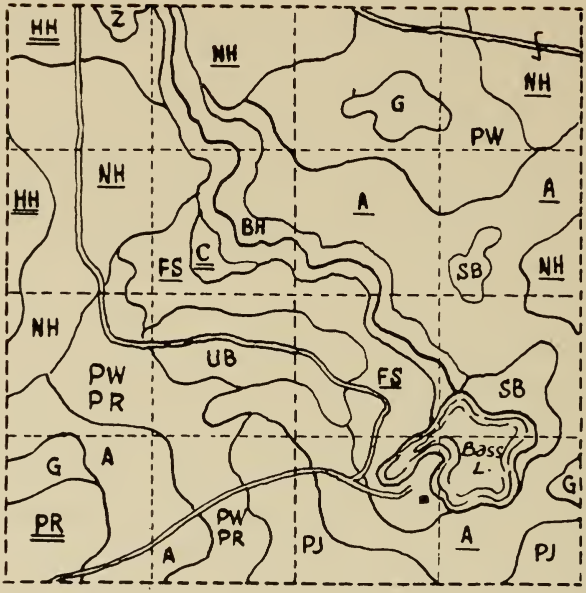


Fig. 14–2. A map of a section (1 square mile) showing water courses, roads, boundaries of forest stands, and other features facilitating the location of soil boundaries.

forest tract and, in the course of this process, to select representative areas for sample plot studies.

The task of the reconnaissance is facilitated if the surveyor proceeds concentrically from broad relationships and large acreage to specific details and small areas. Depending upon the size and the nature of the area, reconnaissance requires between a few hours and two weeks.

Occasionally it may be imperative at the outset to subdivide large tracts into sections requiring surveys of different degrees of intensity. In too many instances soil surveys are conducted in a routine manner which follows dogmatically the pattern of legal subdivision. Such surveys, neglecting the requirements imposed by special physiographic and silvicultural conditions, are insufficiently accurate on some areas but unnecessarily detailed on other areas; their cost may be prohibitive for a private forestry enterprise. As a rule, large areas under agricultural use, as well as swamps, marshes, flood plains, and other lands of minor importance to forest management, can be eliminated from the actual surveying on the basis of existing maps or can be surveyed with a greatly reduced intensity. On the other hand, areas proposed for artificial reforestation should be delineated for an especially detailed mapping. In surveys of several million acres,

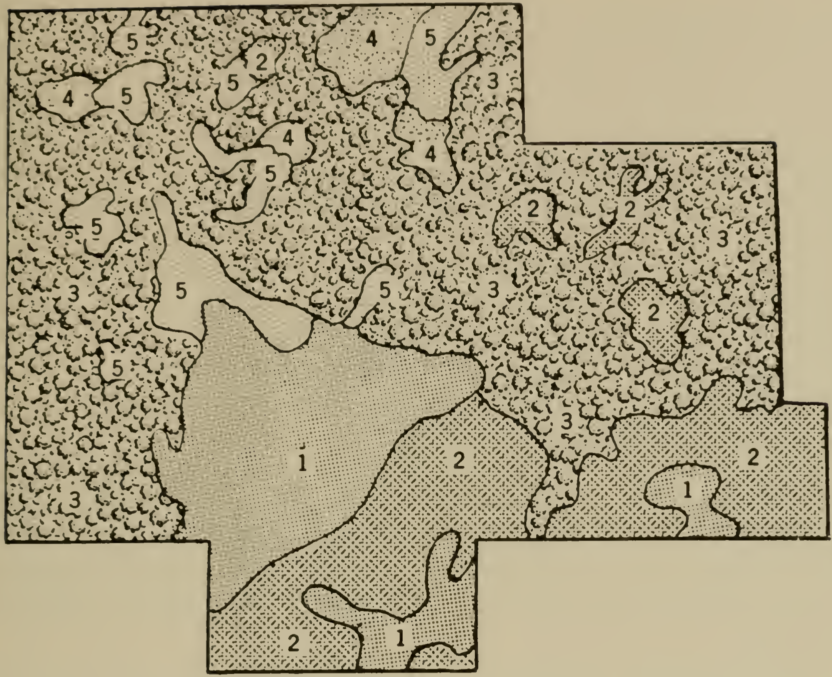


Fig. 14–3. A subdivision of a large area (Langlade County, Wisconsin) into land types to be surveyed for forestry purposes at different intensities: (1) stone-free level outwash silt loams utilized by farming and therefore largely excluded from the forest survey; (2) rolling silt loams partially in farming use; survey to be confined to individual woodlots; (3) rough and stony lands of moraines supporting hardwood-coniferous stands to be managed by selection cuttings; fairly intensive survey at intervals of ¼ mile; (4) outwash sandy plains in need of artificial reforestation; intensive survey at intervals of ⅛ mile; (5) swamp lands to be incorporated into the map from aerial photographs after identification of the origin of peat deposits.

witnessed by the author, nearly one-third of the effort was spent in crossing muskegs, nearly impenetrable cedar swamps, beaver flowages, and rocky grounds of commercially worthless timber line forest. A set of aerial photographs could have saved many thousands of miles of unnecessary walking. Fig. 14–3 illustrates a broad subdivision of the land in the glaciated region of Wisconsin.

Sample plot investigations. The selected sample forest stands must be uniform in their floristic composition, including trees, shrubs, and ground-cover vegetation. These sample areas are usually chosen within the surveyed tract, but in the case of deforested lands they may be located in the surrounding territory. Sample plots, varying in size from one-half to 2 acres, are laid out in well-stocked portions of the stands, and floristic and mensurational records are taken (Spurr, 1952). In doing so, particular attention is paid to the determination of the average height and the site index of the stand, and to the identification of the characteristic features of the ground-cover vegetation (Wilde, 1954). These analyses are followed by a careful investigation of the soil profile. Ordinarily, two or three sample plots in each forest type are sufficient to reveal the main features of soil and forest growth and determine soil types to be surveyed.

The established types may eventually be further subdivided in accordance with the needs of silvicultural practice. For instance, a melanized loam supporting a hardwood stand with a ground cover of maidenhair fern type may be divided into two subtypes: level outwash loam, permitting furrow planting, and rolling stony morainic loam, requiring spot planting.

In establishing survey units it is of utmost importance to remember that all the separated areas must possess essential differences in one of the following aspects: adaptation of soil to tree species, actual or potential rate of stand growth, possibilities of natural reproduction, method of tree-planting, technique of thinning and selection cuttings.

Nomenclature. Soil types or sites are designated on the basis of the location of a representative area of the type, suitability of the soil for certain tree species, characteristic ground cover, or genetical and morphological properties of soils.

Naming soil types after a certain locality or town, for example, **Vilas sand** or **Miami loam**, is the easiest way to classify a great variety of soil types. It eliminates the necessity of using long descriptive names and permits classification of thousands of soil types without danger of terminological confusion. However, a map provided with a legend of this kind cannot be interpreted without an accompanying report and is inconvenient in the field. This system has thus far failed to attain popularity among practicing foresters.

Designation of sites according to their adaptation to characteristic tree species, such as **jack pine site, spruce site,** or **lowland hardwood site,** is most useful on the map showing tree-planting possibilities. Designation of this kind meets with the enthusiastic approval of practicing foresters because of its simplicity. Nevertheless, the presentation of the entire survey in terms of planting sites often may not be desirable, because soils suitable for the planting of the same species (or supporting stands of the same composition) may vary greatly in their productive capacity.

Designation of soils on the basis of the characteristic ground-cover vegetation, for example, ***Vaccinium*** **site, fern site,** or **wood-sorrel site,** is very convenient in surveys of extensive forest tracts supporting mature forests or swamp forests. In surveying tracts with large areas of cut-over land or young second-growth stands, a purely floristic legend may lead to serious misinterpretations.

Finally, soils may be designated by simple morphological or pedogenetical terms, for example, **leached sand, podzolic sandy loam, shallow-gley loam,** and **structured clay.** This type of soil designation may be facilitated by the use of the following more or less conventional adjectives: gravelly, skeletal, stony, barren, melanized, podzolized, degraded, friable, compacted, indurated, cemented, subirrigated, puddled, water-logged, phreatic, vadose, inundated. These terms may be further supplemented by words referring to the geologic origin of soils, such as aeolian, alluvial, lacustrine, outwash, morainic, esker, drumlin, residual, eroded, and overwashed. The organic deposits are classified according to their origin as **muck, sapropel, sedge peat, woody peat, moss peat, brown** or **green moss peat, moss mor,** and **half bog.** At times it is necessary to employ additional designations, derived from purely topographic location of soils, for example: ridge, crest, slope, cove, glade, swale, terrace, streambottom, kettle, and so on.

For the sake of brevity the surveyor of forest soils should avoid the long and often unnecessarily complicated designations of the textural soil classes, such as "very fine sand," "fine sandy loam," and "silty clay loam." As a rule, all important textural features of forest soils can be covered by a few divisions, e.g., sand, loamy sand, sandy loam, nearloam or light loam, loam, and clay. Whenever possible, the designation of soils should be supplemented by terms used by the State and Federal Soil Survey divisions.

As often as not, the choice of terminology is dictated by the personal preferences of the owner of the forest tract or the supervising officer. Otherwise, the terminology must be brief and reasonably expressive; in the particular case of forest-soil survey it represents only conventional labels which stand for the whole complex of properties of the surveyed soils. An attempt to maintain the designation of surveyed soils on a scientific pedogenetic or other basis would invariably lead to cumbersome and often ambiguous expressions, such as "humus-illuvial gley podzolic sandy clay" (Gerasimov, 1952). But even if we should accept terms of this length, it would not be possible to meet the requirements imposed by the survey of forest soils; the languages of the world still do not possess even half of the soil terms needed to express the conditions of forest growth.

Report on survey of forest soils. The map of forest soils types or sites must be accompanied by a report, written in concise, carefully worded language. This report should include the general characteristics of the surveyed area, such as its geographic location, important climatic data, nature of the surface geologic formations and underlying rocks, mineralogic composition of parent soil materials, and hydrologic features. Next, an account should be given of the technique of mapping employed, including a statement on the intervals at which the land was traversed, the reliability of controls, the number of soil profiles investigated, the frequency of borings, and the extent of laboratory analyses. A detailed description of each soil-forest unit should embrace composition of the soil, position and properties of ground water, influence of runoff and seepage water, composition of main forest stand and understory, quantitative appraisal of the ground-cover vegetation, approximate rate of forest growth or the site quality index. It is also highly desirable to state the possibilities of natural reproduction by seed and sprouts, competition of weed or undesirable species, suitable systems of silvicultural management, types of thinnings and selection cuttings, species important in conservation and fire protection, feasibility of artificial reforestation, tree species suitable for planting, and suitable planting methods.

It is advisable to attach to the report schematic drawings of representative soil profiles indicating the minimum and the maximum depths of genetic soil horizons. Such drawings should emphasize the morphology of the humus layers and the occurrence of impervious or hardpan layers, strata with a high content of carbonates, and waterlogged gley horizons. Fig. 14–4 gives an example of a forest soil map. A sample description of a soil type, borrowed from the records of the Consolidated Water Power and Paper Company, follows.

Sample description of a surveyed soil type (subirrigated sandy loam podzol of Saugatuck series). This leached and hydromorphic soil of level and pitted outwash has a conspicuous, readily identifiable morphology.

F + *H* 0 to 2.0 ± 0.5″. Matted ligno-mycelial mor. Rea., pH 4.5; catalytic capacity, 12 mm. Hg; color, 5 YR 2/2.

A_2 2 to 14 ± 1.5″. Strongly leached, light gray, nearly white, siliceous sandy loam, occasionally stained with dark humate suspensions. Rea., pH 4.7; silt and clay content, 12.7 p.ct.; color, 7.5 YR 8/0.

B 14 to 27 ± 3″. Rusty red to coffee brown sandy loam, penetrated by terminal tasseled roots and exhibiting slight mottling in the lower part of the horizon. Rea., pH 4.9; silt and clay, 18.5 p.ct.; air permeability, 54 mm. Hg; color, 7.5 R 4/8 to 3/4.

G 24″ plus. Orange gray, strongly mottled, waterlogged siliceous coarse sand. Rea., pH 5.0; silt and clay, 7 p.ct.; color, 7.5 R 6/6.

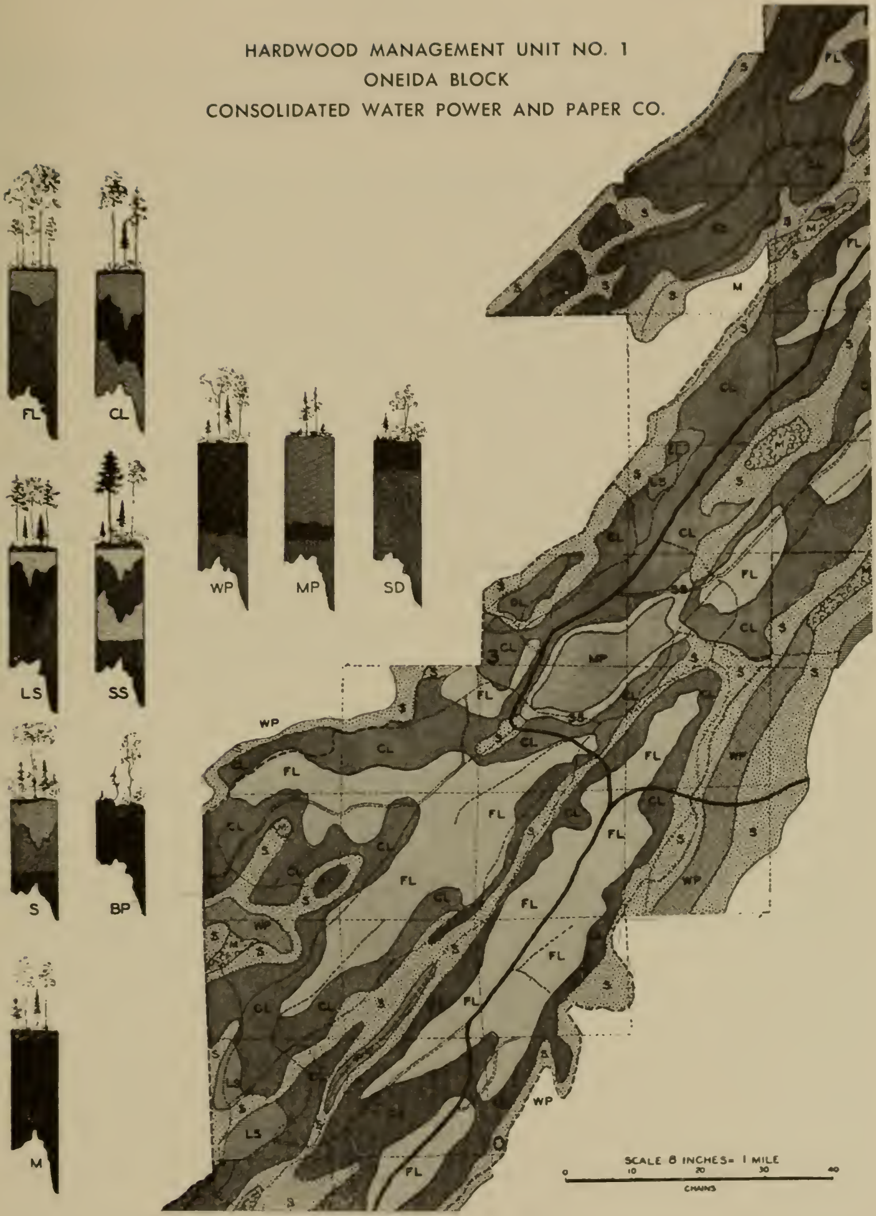

HARDWOOD MANAGEMENT UNIT NO. 1
ONEIDA BLOCK
CONSOLIDATED WATER POWER AND PAPER CO.
FL
CL
WP
MP
SD
LS
SS
S
BP
M
SCALE 8 INCHES = 1 MILE
0
10
20
30
40
CHAINS

FIG. 14–4. A forest soil map showing a portion of the management unit. Legend: FL—friable loam: hardwoods; CL—compacted loam: hardwoods and conifers; S—puddled soils of swales: lowland hardwoods and conifers; LS—leached sandy loam: hemlock, yellow birch; SS—subirrigated sandy loam: white pine, balsam fir, white spruce; M—moss mor: white cedar, hemlock, balsam fir, black ash, red maple; BP—boulder pavement: paper birch; WP—woody peat: black ash, white cedar; MP—moss peat: black spruce, tamarack; SD—stream bottom deposits: tag alder, willows, elms, spruces, and balsam fir. (Surveyed by E. S. Hurd, J. W. Macon, R. S. Pierce, W. White, and S. A. Wilde.)

> Ground water at the time of examination is at the depth of 30″. Its analysis: Rea., pH 5.3; redox potential, −127 m.v.; specific conductance, 0.12 millimhos.

The state of fertility factors, as expressed by the composition of the surface 6-inch layer of soil, is characterized by the following average results: organic matter, 3.5 p.ct.; exchange capacity, 8.7 m.e. per 100 g.; total N, 0.93 p.ct.; available P_2O_5, 52 lbs/A.; available K_2O, 147 lbs/A.; exchangeable Ca, 2.3 m.e. per 100 g.; exchangeable Mg, 1.1 m.e. per 100 g.

The virgin forest consisted of white pine with understory of balsam fir and white spruce, and with ground cover of *Cornus-Maianthemum* type. The remnants of the original cover indicate that logging removed between 25 and 35 Mbf per acre. The pioneer stands, approximately 40 years old, are composed of balsam fir with some white spruce, black spruce, trembling aspen, paper birch, and red maple. The shrub layer of hazelnut, black berries, dogwood, willows, and bush honeysuckle is confined to stands including deciduous trees.

The ground cover vegetation includes largely raw humus species. Its composition is outlined by the following average D/F quotients, where D is density or the number of plants of a certain species per 100 linear feet, and F is frequency or the percentage of occurrence of a species in 10-foot segments: *Cornus canadensis*, 108/75; *Maianthemum canadense*, 36/48; *Pteridium latiusculum*, 29/31; *Clintonia borealis*, 14/52; *Lycopodium* spp., 14/37; *Coptis trifolia*, 12/29; *Oxalis montana*, 7/10; *Linnaea borealis*, 6/8; some *Rubus villosus, Aster macrophyllum, Galium triflorum*, and *Fragaria virginiana*.

The yields of 40 year old, fully stocked stands of balsam fir approach 25 cords per acre; the participation of aspen and other deciduous species decreases the volume to about 18 cords per acre. The maximum productive potential of this soil type at the end of rotation (60 years) is estimated between 35 and 45 cords per acre.

The silvicultural management of the second-growth stands is largely limited to the production of pulpwood. The first cut is determined by the density of the stand and to some extent by the demand for Christmas trees. The second, regeneration cut is feasible at the age of 35 to 40 years. It should be conducted to improve the structure of the stand and to recover a part of the investment by the removal of some merchantable, bigger but not necessarily best trees. A release of promising spruce specimens and a gradual increase of the spruce fraction is an important detail of this cutting operation. The extraction of the logged material during the snowless period will encourage the establishment of the natural regeneration. Occasionally, this process can be enhanced by a mechanical scarification of the soil. The final cut at an approximate age of 50 to 60 years should release advanced natural reproduction and may be combined with a weeding cut removing Christmas trees.

The adverse conditions which restrict freedom of silvicultural operations on this soil type are: instability of the ground water table, shallow anchoring of root systems, especially that of spruce, short life span of balsam fir, and vulnerability of soil to invasion of *Sphagnum* moss. The latter takes place when heavy cutting increases the content of soil moisture through the reduction of the interceptional and transpirational effects of the canopy. Tree planting on open areas is handicapped by periodic excess of soil moisture, danger of frost injury, and competition of grass. Fortunately, the need for artificial reforestation is seldom encountered on this soil type.

The possibility of forest exploitation on short rotations and the ease of natural forest regeneration are the favorable conditions which place subirrigated sandy loams among the attractive types for private forestry enterprise.

Use of soil survey in forest management. The soil types delineated by the survey usually serve as the units of forest management, called "compartments" or "lots." Depending on circumstances, the forester in charge may either combine into one compartment several soil types occupying small areas, or he may subdivide extensive areas of the same type into a number of compartments. When a compartment includes a number of soil types, each is treated as a "subcompartment." The subdivision into subcompartments may also be necessary because of differences in the origin, age, or composition of forest cover.

The compartments are customarily designated by Arabic numbers and subcompartments by small letters. Such a system of designation helps greatly to keep a permanent, orderly record of all the data pertinent to the growth and silvicultural treatment of individual forest stands. Table 14–1 gives an example of stand inventory comprising a part of a management plan.

TABLE 14–1

A SAMPLE OF A STAND INVENTORY

Unit	Composition of soil	Composition of stand	Area (acres)	Age (yr.)	Site index	Remarks
7a	Podzolic sandy loam; level outwash	0.8 white pine^4, red pine^1, aspen^5	17.3	22	70	Release cutting due
7b	Same as Unit 7a	Recently burned area	5.5	. . .	. . .	To be planted to red pine in 1957
7c	Swamp-border sandy podzol	0.7 white pine^3, white spruce^1, balsam fir^2, aspen^4	3.4	22	50	No treatment until 1960

In the event that the forest tract is composed of several large areas of widely different conditions of physiography and forest cover, such areas are treated as independent management units. Heavy morainic deposits with hardwood stands, attaining suitable dimensions at the age of eighty years, and sandy outwash, producing jack pine pulpwood at forty years, may be given as examples of two management units.

Broader aspects of soil surveying. The importance of soil survey is not limited to its immediate utilitarian purpose of facilitating an efficient management of timber lands. The process of surveying carries the participants through a rigorous study of the cause and effect relationship, the functional interdependence between environmental influences and vegetation responses. This type of postgraduate work in the laboratory of Nature advances the surveyor from the rank of a *taught* technician to that of a *learned* specialist, a man whose firsthand knowledge once inspired the following statement of Emerson (1851):

> Is it not a convenience to have a person in town who knows where pennyroyal grows, or sassafras, or punk for a slow match; or Celtis—the false elm; or cats-o'-nine-tails; or wild cherries; or wild pears; where is the best apple tree, where is the Norway pine, where the beech, or Epigaea, or Linnaea, or Sanguinaria, or Orchis pulcherrima, or Drosera, or Laurus benzoin, or pink huckleberry, or shagbarks; where is the best chestnut grove, hazelnuts . . .

More than any voluminous text, this paragraph of a mere taxonomic enumeration has influenced the development of American forestry, ecology, land conservation, and soil surveying. For it is generally acknowledged that Emerson is to American life what Shakespeare is to British and Goethe to German (Lindeman, 1954).

15

Hitherto I had never seen so extensive a walnut forest in Auvergne . . . it constitutes all the wealth of the district, for it is planted on common land. Formerly this land was a hill-side covered with brushwood and barely sufficed to feed a few sheep. —Guy de Maupassant

Soils and reforestation

The experience of recent years has shown that in many instances the survival of planted trees leads to much greater financial losses than their failure. A slow-growing plantation is a liability rather than an asset; such a plantation devours the cost of upkeep as well as the interest on the investment. Therefore, reforestation accomplished without regard to the productive potential of soils often represents pseudoconstructive effort creating negative values. Besides being the cause of financial losses, misplaced plantations serve as breeding centers for parasites and thus threaten large-scale destruction of forest stands (Fig. 15–1).

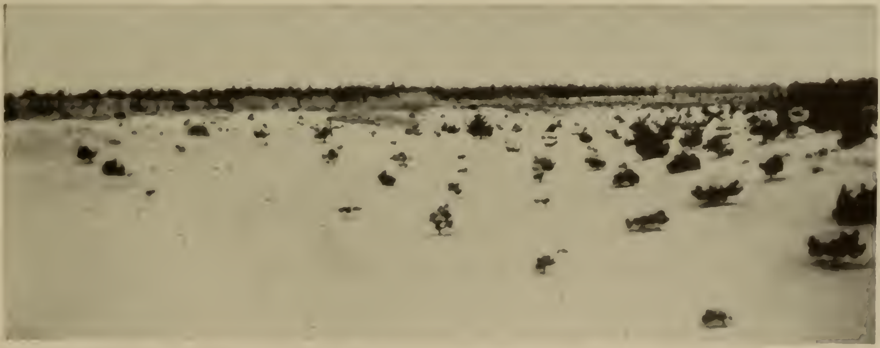


FIG. 15–1. An illustration of a fruitless reforestation effort—planting of red and white pines on a wind-blown sand totally devoid of organic matter. The perishing plantation is 6 years old.

In order to avoid hidden pitfalls of reforestation, attention must be given, not only to the mere survival of planted trees, but also to other important aspects of the plantation existence. The supply of water, air, and nutrients in the selected soil must offer planted trees a fair chance to withstand the attacks of parasites, permit future natural regeneration of the established plantation, and favor the production of high-grade timber or pulpwood at a reasonably rapid rate (Burger, 1931; Heiberg, 1933; Wittich, 1948).

The reforestation program in a given region includes the following major steps: the selection of species suitable for planting, production of planting stock, selection of planting sites, and the actual planting.

SELECTION OF TREE SPECIES

Species for planting are usually selected by the chief administrative officer responsible for the reforestation of a large territory, such as a state or national forest. The conditions of climate and soils, resistance to insects and diseases, and the commercial importance of the species are the principal points considered in the selection (Toumey and Korstian, 1947).

In order to facilitate the location of nurseries and the proper distribution of stock, extensive regions are sometimes roughly divided into several areas adapted to a certain combination of tree species or a specific type of reforestation. Figure 15–2 gives an example of such broad division on the basis of climate and soils.

The seed of the chosen species is acquired from reliable sources and used either for direct seeding or for raising planting stock in nurseries. In the majority of cases the selection of trees to be planted is confined to native species, the seed or cuttings of which are procured in the region where the planting is proposed, or at least from ecologically similar areas. The planting of species introduced from abroad or from other sections of the same country is hazardous and must be carried on with rigid observance of the rules of acclimatization (Mayr, 1909; Bühler, 1922; Ilvessalo, 1926; Hartmann, Querengässer, and Jahn, 1953). The wholesale destruction of Norway spruce stands of central Europe by nun moth, spruce beetle, and parasitic fungi has given convincing evidence of the hazard involved in the violation of site requirements. While the danger of the introduction of "foreign" or "exotic" species is usually emphasized, little consideration is given to the shifting of "native" species within the boundaries of a political unit, even though such a translocation sometimes involves greater changes in environmental conditions. A 200-mile translocation of white spruce from northern to southern

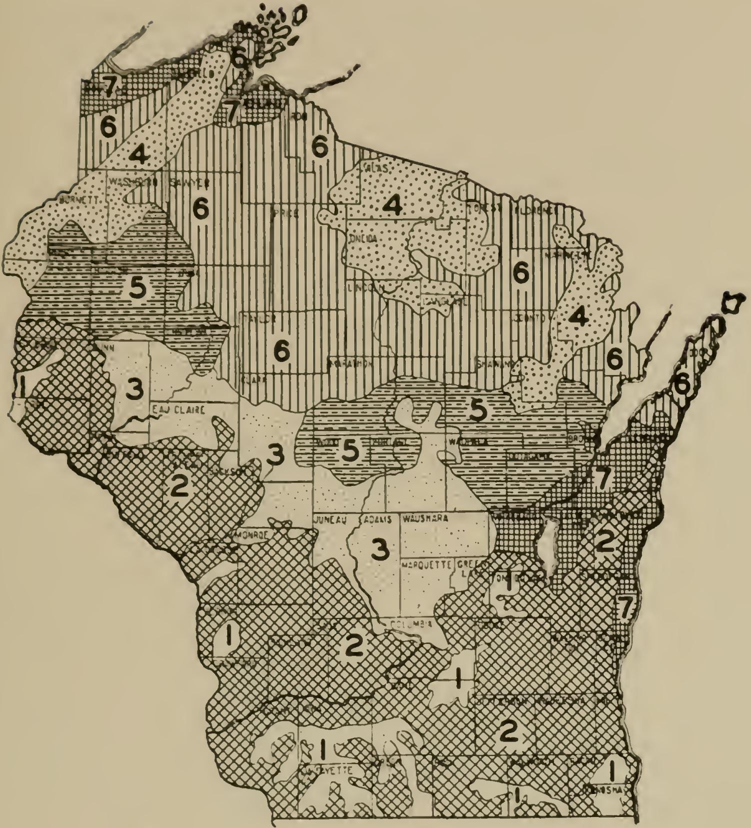


Fig. 15-2. A broad subdivision of a region (state of Wisconsin) for reforestation purposes: (1) *prairie soils*—tree planting limited to shelterbelts, game cover, and erosion control; (2) *silt loams derived from limestone, calcareous drift, and loess*—white and green ash, hard maple, basswood, black walnut, hickory, oaks, and white and red cedar; (3) *sands and sandy loams of siliceous origin*—jack pine, red pine, and white pine; planting of other species confined to small areas underlain by lacustrine clay; (4) *sands and sandy loams of granitic origin*—jack pine, red pine, white pine; planting of spruce confined to areas with boulder clay substratum and accessible ground water; (5) *slightly leached loam soils*—hard maple, basswood, white ash, red oak, white pine; (6) *strongly leached loam soils*—spruce, yellow birch; planting of hardwoods confined to areas of slightly acid mull soils; (7) *lacustrine clays*—white pine, white cedar, white and rock elms, yellow birch; in the eastern portion also white ash. Planting is often handicapped by the unfavorable physical properties of the soil, heaving, and high content of lime in the substratum, and must be investigated in each individual case.

Wisconsin may present a much more difficult problem of acclimatization than the 5000-mile translocation of Scotch pine from the Danube Valley to central Wisconsin. Thus, a "foreign species" in a political sense may be a "native species" in an ecological sense, and vice versa.

The first rule of acclimatization is to confine the translocation of species to the boundaries of their native genetical soil groups.

SELECTION OF PLANTING SITES

As a rule, the selection of planting sites constitutes a part of the forest soil survey which covers the entire management unit. Otherwise, areas suitable for planting of the available nursery stock are selected periodically according to the existing need. The sites for spring and fall planting are usually selected the preceding fall and summer, respectively.

The most important factors to be considered in the selection of planting sites are enumerated in the following outline:

> **Site factors:** Exposure to sun and wind, distribution of rainfall, depth and duration of snow cover, accumulation of cold air in depressions, danger of plantation injury by winter kill, frost, drought, and sunscald. Position of the area in regard to inundation. Vulnerability of soil to erosion.
>
> **Soil factors:** Height of the ground water table, extent of capillary fringe, and saturation of soil in spring. Soil texture and structure; permeability of soil to air and water, moisture content and aeration in critical periods, danger of frost heaving, possibility of leaving air pockets in the planting hole. Depth to impervious layers, such as hardpan, claypan, or rock substratum, and the effect of these layers on root development. Danger of drought, periodic stagnation, and windfall. The content of soil organic matter, reaction of soil, and supply of essential nutrients. Occurrence of layers high in carbonates, soluble salts, and toxic substances.
>
> **Biotic factors:** Competition of herbaceous and woody vegetation; protective and suppressing effects of nurse stand. Danger of injury by rodents, game, and livestock. Ability of planted trees to form stable and harmonious union with native trees, shrubs, ground-cover vegetation, and lower plant forms. Occurrence of insect and fungal vectors and danger of parasites. In reforestation by the use of direct seeding or cuttings, presence of mycorrhizal fungi and other symbiotic microorganisms.

In addition to ecological conditions, a number of purely economic factors, such as recreational value of the area, transportation facilities, and danger of fire, must be considered in the selection of planting sites.

Because the significance of soil factors varies considerably under different climatic conditions and with different ecological varieties of the same species, only general suggestions can be given in regard to the suitability of soils for planting various trees. Table 15–1 presents approximate data on the depth to ground water, soil texture, content of organic matter, and reaction of soil related to the planting of several silviculturally important coniferous and hardwood species. It should be stressed that success in planting cannot be assured with species having only medium or low ability to survive on exposed cut-over areas unless such species are planted under the protection of a nurse stand (Stoeckeler and Limstrom, 1942). The stated mini-

TABLE 15-1

PLANTING-SITE REQUIREMENTS OF TREE SPECIES COMMONLY USED IN REFORESTATION

Tree species	Survival on exposed areas*	Min. depth to ground water table (ft.)	Range of optimum reaction (pH)	Minimum content of silt and clay particles (%)	Minimum content of organic matter in 6-in. layer (%)
Ash, green	Medium	3.5	6.0–8.0	25	2.5
Ash, white	Medium	2.5	5.5–8.0	40	4.0
Aspen, largetooth	High	2.0	5.5–7.0	15	2.5
Basswood	Low	3.5	5.5–7.5	40	3.0
Birch, yellow	Medium	2.0	4.7–6.5	25	2.5
Cedar, red	High	3.5	5.0–8.0	None	0.7
Cedar, white	Medium	1.0	4.7–8.0	40	4.0
Cherry, black	Medium	2.5	5.0–7.0	25	1.5
Cottonwood	High	1.0	5.5–8.0	15	1.8
Elm, rock	Medium	2.0	5.0–6.5	40	3.0
Elm, white	Medium	2.0	5.0–8.0	25	2.5
Fir, balsam	Low	1.5	4.7–6.5	25	3.0
Fir, Douglas	Medium	2.0	5.0–7.5	15	1.8
Hickory, shagbark	High	3.5	5.5–8.0	25	2.5
Locust, black	High	3.5	6.0–8.0	25	None
Maple, hard	Low	3.5	5.5–7.5	40	3.0
Oak, northern red	Medium	2.5	5.0–7.0	25	3.0
Oak, white	Medium	3.5	5.5–8.0	40	4.0
Pine, jack	High	2.5	5.5–7.0	5	0.7
Pine, lodgepole	High	2.5	5.5–7.0	5	0.7
Pine, longleaf	High	2.0	4.5–6.0	None	None
Pine, ponderosa	High	3.5	5.5–8.0	5	1.2
Pine, red	Medium	3.5	5.0–6.5	10	1.8
Pine, Scotch	High	3.5	4.7–6.0	10	0.7
Pine, shortleaf	High	2.5	4.5–6.0	10	0.7
Pine, eastern white	Low	2.5	4.7–7.5	15	2.5
Poplar, tulip	Medium	2.5	5.5–7.5	40	1.8
Spruce, Norway	Low	2.0	4.7–6.5	40	4.0
Spruce, white	Medium	2.0	4.7–6.5	25	3.0
Walnut, black	Low	3.5	6.0–8.0	40	4.0

* This rating would be less rigorous in humid and frost-free environments.

mum contents of silt and clay particles may be somewhat high for planting on soils with a high ground water table or in a humid climate. However, even under such conditions it is not advisable to lower the standards without urgent need, for the content of colloids is usually related not only to the water-holding capacity of soil but also to the content of available nutrients.

As has been stressed elsewhere (Wilde, 1954), the silvicultural importance of soil reaction is not directly related to either the concentration or the activity of H and OH ions. The significance of the pH value lies in its ability to indicate several unsatisfactory conditions of soil or site, such as poor soil structure, presence of hardpan layers, disrupted availability of nutrients, occurrence of parasitic fungi, and potential competition of weeds. Therefore, the narrow reaction range given in the table aims to express the limitations which may be encountered under adverse climatic and soil conditions. In favorable environments, the range of suitable pH values may be considerably extended, especially in the direction of soil acidity.

Ordinarily, the supply of available nutrients is closely correlated with the content of colloids, organic matter, and the pH value of the soil. In the majority of cases, therefore, a detailed chemical analysis of soil can be omitted in the selection of planting sites. In a broad way, chemical composition and potential fertility of soils not appreciably altered by podzolization or laterization may be estimated on the basis of the geologic origin of soil, as indicated in Table 15–2. However, in reforestation of soils derived from siliceous rocks or deposits, burned-out peat soils, and especially soils subjected to previous agricultural use, the presence of an adequate supply of essential nutrients must be ascertained by analyses of representative soil samples. Such analyses are particularly desirable in regions showing poor growth of native stands or plantations. As a rule, the analysis could be limited to the upper 6-inch layer of soils, as its composition usually reflects the properties of the substratum and is of decisive importance in the initial growth of planted trees. In some instances, however, it may be necessary to analyze the lower soil layers, provided that they occur at a depth which can be reached by the roots of seedlings within a few years. The roots of cottonwood or some other deciduous species may reach a fertile substratum located as deep as 6 or 7 feet during the second growing season after planting. The available data on the minimum fertility levels necessary for a satisfactory growth of different groups of trees are given in Table 15–3. The contents of nutrients required by trees in forest plantations are very low in comparison with agricultural or

TABLE 15-2

RELATION OF GEOLOGIC ORIGIN OF SOILS TO THEIR POTENTIAL PRODUCTIVITY AND TREE-PLANTING POSSIBILITIES

Nature of parent soil material	Probable composition of soil	Reforestation possibilities
SILICEOUS ROCKS Sandstone Quartzite Siliceous shales	Low content of nutrients, especially phosphorus and potassium	Pines and less-exacting deciduous pioneer species
FELDSPATHIC ROCKS Granite Syenite Gneiss	Adequate content of nutrients with possible exception of lime	Conifers and hardwoods with the exception of pronounced lime-demanding species
FERROMAGNESIAN ROCKS Diorite Diabase Basalt	High content of nutrients, especially calcium and magnesium	Hardwoods; conifers, particularly spruce, tend to produce high yields but in warm regions suffer from fungus diseases
CALCAREOUS ROCKS Limestone Dolomite Calcareous shales	High content of lime; possible deficiency of potassium and phosphorus	Lime-tolerant trees, e.g.: oaks, hickory, walnut, ash, beech, red and white cedar, ponderosa pine, Austrian pine. Planting of the majority of conifers is questionable outside of superhumid climate.

TABLE 15-3

MINIMUM CONTENTS OF ESSENTIAL NUTRIENTS NECESSARY FOR A SATISFACTORY GROWTH OF REPRESENTATIVE TREE SPECIES IN PLANTATIONS

Tree species planted at a spacing 5 × 5 feet	Content of nutrients in the surface 6-in. layer of the soil				
	Total N (%)	Available P_2O_5	Available K_2O	Exchange Ca	Exchange Mg.
		(lb. per acre)			
Microtrophs [*]	0.02	Tr.	30	200	50
Mesotrophs [†]	0.05	20	50	500	120
Megatrophs [‡]	0.10	50	125	1200	300

[*] Species of low nutrient requirements which produce satisfactory yields on coarse sandy soils, especially pioneer pines, such as longleaf pine, jack pine, and Scotch pine.

[†] Species of moderate nutrient requirements commonly inhabitating sandy loams or heavier soils, viz., white pine, white and black spruce, Douglas fir, European larch, northern red oak, yellow birch, largetooth aspen.

[‡] Species of high nutrient requirements which are usually confined to fine-textured soils, soils enriched in humus, or soils influenced by hard ground water, e.g., black walnut, white ash, hard maple, basswood, white oak, beech, tulip poplar, black locust, Norway spruce, white cedar, and bald cypress.

forest nursery standards because trees in plantations derive their nutrients from a much greater volume of soil than do field crops or nursery stock.

As has already been stressed, the given values of different soil factors may need certain corrections under local conditions. Nevertheless, the standards for the selection of planting sites, based on quantitative analyses, form the basis of the entire tree-planting program. Observation of numerous plantations testifies that haphazard reforestation brings about inadequate increment, financial losses, deterioration of soils, and the spread of parasitic organisms.

Many reforestation mistakes have been made in the past by planting tree species that originally grew on the area; this approach of "tradition" often violates the principles of both forest succession and crop rotation. A still greater number of misplaced plantations owe their origin to reforestation procedures which were guided by "intuition" rather than by analysis of site factors. Occasionally the site requirements of planted trees were disregarded because reforestation was conducted by public agencies which were not particularly concerned in the return of the investment. Private enterprises dependent upon the balance sheet of dollars and cents are likely to subject tree-planting techniques to the scrutiny of efficiency experts. Beyond a shadow of a doubt, the income derived throughout the world from artificial reforestation will rise in direct proportion to the improvement of methods of soil analysis and correct interpretation of analytical data.

METHODS OF TREE PLANTING

In many cases the choice of the proper method of planting is just as important as the selection of species to be planted. This section discusses the main features of the common planting methods (Fig. 15–3) and reviews their adaptation to different soils and sites.

Slit planting. A slit about 10 inches deep is made by means of a planting bar; the roots of the seedling are placed in the slit, and the slit is closed by another thrust of the bar and the planter's heel. In this type of planting the roots are forced during the first season to feed and absorb water in one vertical plane. Long roots must be pruned to a length corresponding to the depth of the slits. In gravelly soils which resist the penetration of the planting bar, the root system is usually reduced beyond reasonable limits. In heavy soils air pockets are often left in closed slits and the roots are exposed to drought. Satisfactory results with this method, therefore, may

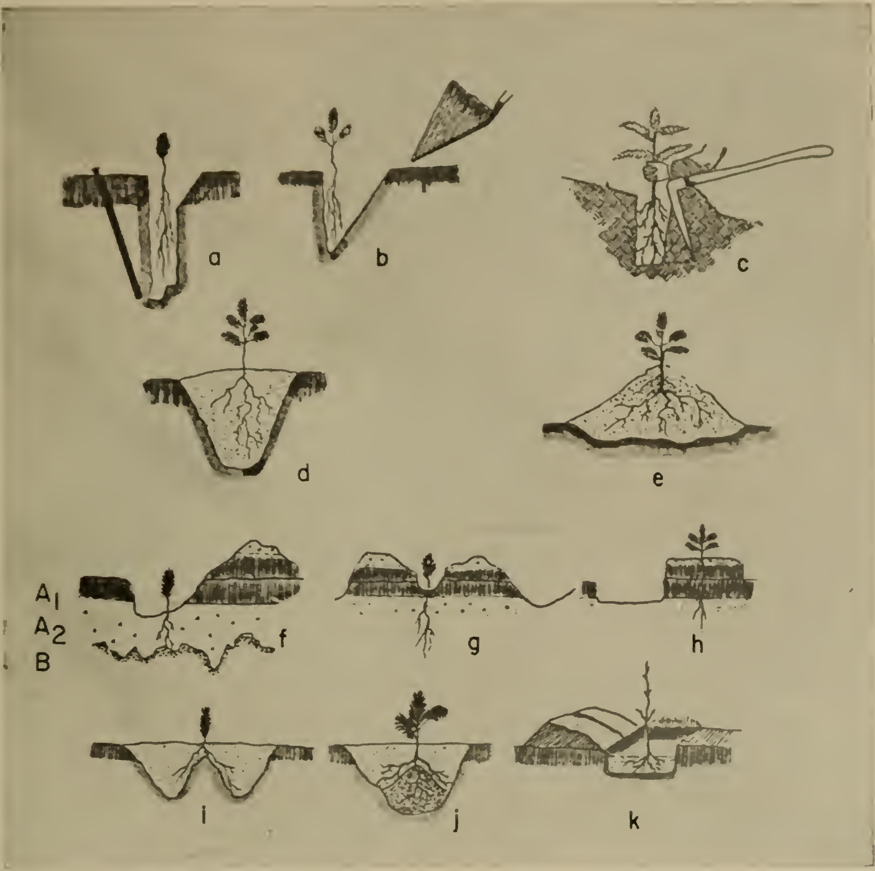


FIG. 15–3. Methods of tree planting: (*a*) slit planting; (*b*) spade planting; (*c*) grub hoe planting; (*d*) hole planting; (*e*) mound planting; (*f*) furrow planting; (*g*) double furrow planting; (*h*) planting on turned sod; (*i*) "inverted V" planting; (*j*) cone planting; (*k*) sod cover planting.

be obtained only on stonefree sandy soils; on such soils slit planting is the cheapest method that compares favorably with elaborate hole planting.

In the reforestation of mountain soils, planting is preferably accomplished by the use of a grub hoe or mattock. Sometimes the planting bar is replaced by a spade which is used to remove a wedge-shaped portion of soil. The roots of the seedlings then are spread against the vertical side of the hole, the wedge of soil is placed in its original position and thoroughly stamped with the foot. This modification of slit planting reduces the danger of leaving air pockets, and it may be applicable to soils which are fairly heavy in texture.

Hole planting. The mattock, grub hoe, shovel, or spade is used to dig a hole slightly larger than the extension of the seedling roots. The seedling is held in position with the roots well distributed in the hole. The hole is then filled with the top soil which is thoroughly packed with the foot. Hole planting enables the seedlings to utilize larger quantities of moisture and nutrients in the earlier stages of growth and is considered to be one of the most reliable methods (Dengler, 1930). It is adapted to a wide range of soils, including those of stony or gravelly nature. Strongly leached cemented podzol soils, very shallow residual soils, and soils with a high ground water table are exceptions. Hole planting allows the mixing of additional fertile soil or the use of fertilizing materials.

Mound planting. The sod layer is removed with a spade or mattock, and a mound is made from surface soil collected nearby. The seedling is planted by hand with the roots spread as much as possible. Sometimes the mounds are prepared a year in advance of planting, and a dibble or a spade is used to make the hole for the seedlings. A special planting iron devised by Henning is also used to impress a hole in the mound. This iron makes three slit-like holes extending radially downward so that the roots may be spread laterally in their natural position and covered with fertile soil.

Mound planting is of greatest importance in reforesting poorly drained soils where the mounds insure a fair degree of soil aeration for seedlings and reduce frost heaving. Mounds are sometimes used on heavier upland soils in order to place the seedlings in an elevated position and thus give them a better opportunity to compete with weed vegetation. This method may be necessary in planting shallow residual soils, particularly those derived from calcareous rocks. It is advantageous on podzol soils underlain by a hardpan horizon. On soils of a light sandy texture wind is apt to destroy the mounds and expose the root system. Some foresters advocated mound planting as a means of increasing survival of plantations in times of drought.

Planting in furrows. Furrows for tree planting are made with a special plow and tractor. The depth of furrows is varied, according to site requirements, from 3 to 12 inches. The planting itself is accomplished by means of mattock, spade, or spud. On tillable soils reasonably level in topography and free from stones the furrowing, as well as the setting of trees, is accomplished by tree-planting machines (Fig. 15–4).

The chief advantages of furrowing are:

1. The plow and tractor destroy the grass, brush, and other competing vegetation

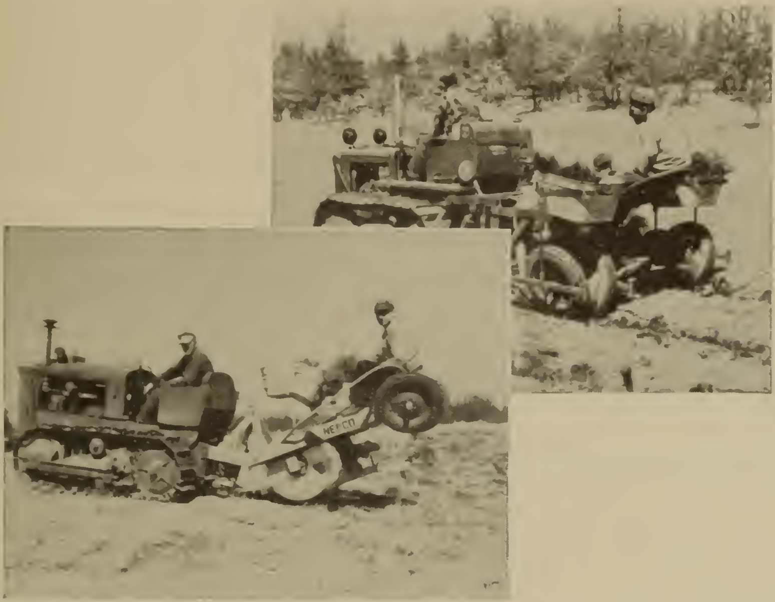


FIG. 15–4. Tree-planting machines of recent design: (*left*) "air-borne" machine which can be lifted to avoid obstacles and to facilitate operation; (*right*) dual machine setting two rows of seedlings simultaneously. (Nekoosa-Edwards Paper Co.)

2. When furrows follow contour lines they retain some run-off water and may thus provide a greater amount of moisture for the seedlings
3. The plowing may help the seedlings to reach the capillary water in a shorter time
4. On exposed sites, deep furrows protect the seedlings from wind and sun

The most serious disadvantages of furrowing are:

1. The plow removes the surface humus layer of the soil, thereby decreasing the water-holding capacity and content of nutrients
2. On heavier soils and in regions subject to early or late frosts, the water accumulated in the furrows may cause frost heaving
3. Plowing may expose toxic or impervious layers, such as hardpan, claypan, calcareous layers, or unweathered rock substratum

Experience has shown that deep furrowing is particularly beneficial in increasing the survival of seedlings on extensive cut-over areas exposed to the desiccating effect of wind and sun (Wilde and Albert, 1942). On sandy soils this increased survival is obtained at the cost of a somewhat lower rate of growth of the plantation during its earlier stage of development. Shallow plowing is beneficial chiefly on heavy mull soils, where it destroys the abundant competing vegetation but leaves a part of the humus layer undisturbed. Planting in furrows is impracticable on podzols and shallow residual soils. Also this method is not feasible on stony soils and areas supporting heavy sprouts. On such areas furrowing should be replaced by scalping. It is important to orient the furrows in such a manner as to provide maximum protection of planted seedlings from both the sun and the prevailing desiccating winds.

On soils supporting a heavy cover of fast-growing grasses, a narrow V-shaped furrow is made with a special 4-inch scooter plow. Two broad furrows are turned inward at a distance of about 2 feet on each side of the scooter furrow. The scooter furrow thus forms a catch basin for rainwater and checks the growth of competing grass.

Planting on turned sod. The seedlings are set on the furrow slice or on the turned-back sod of scalped spots. The purpose of this method is to secure the nutrients and moisture of a double humus layer, to place seedlings in a higher position so as to reduce the competition of herbaceous vegetation, and to provide better aeration on wet sites. Plowing or scalping is done in the fall preceding the spring planting so that the furrow slice or sod layer may settle and produce a uniform solid medium for planting. Seedlings are usually planted with the planting bar.

This method is applicable chiefly in underplanting or in reforestation of small protected cut-over areas. On exposed sites the trees are often destroyed by drought and sunscald. Planting on turned sod is sometimes used in reforestation of podzol areas underlain by an Ortstein horizon. In such plantings the ridge is often made by turning two furrows inward. A similar technique is employed in planting wet soils.

Cone planting. The planting hole is dug with a spade or grub hoe. A conical mound is made in the bottom of this hole, using some of the best soil, and the roots of the seedling are spread over its surface with the hand. More of the best soil is then placed over the roots and packed with the hands. Finally all the remaining soil is added and thoroughly packed. This method of planting provides a greater surface area for contact of the roots with the soil and is suitable to any deep, well-drained soil. It is not adapted for planting trees with a single taproot.

The same objectives are reached by the so-called "inverted V" method in which the hole is dug with two separate downward strokes of a Baldwin planting hoe or a mattock in such a manner that an inverted V-shaped ridge or saddle of soil is left across the hole.

Sod cover planting. A block of sod about one foot square is cut loose on three sides with the spade and turned back. The seedling is planted in the exposed soil. The sod layer is then cut through the middle and folded back into its original position. This method is used on heavy soils subject to frost heaving, especially in planting large-sized stock of deciduous species such as alder, birch, and ash.

DIAGNOSIS OF THE CONDITIONS RESPONSIBLE FOR THE FAILURE OR DETERIORATION OF PLANTATIONS

Unsatisfactory growth of planted trees may be caused by adverse conditions of soil and climate, destructive biotic agents, inferior quality of planting stock, or defective planting technique (Rudolf, 1939). Among the properties of soil the following are of primary importance:

1. Inadequate content of colloids and deficiency of moisture
2. Excess of water and resulting insufficient aeration
3. Wide amplitude of the fluctuating ground water table, responsible for extremes in moisture and air content of the soil
4. Unsatisfactory soil structure due to a high content of clay, cementation or impregnation by translocated colloids, compaction by livestock; cracking or heaving of soils
5. Impermeability of surface soil and the loss of water through evaporation or run-off
6. Deficiency of organic matter, unsuitable reaction, lack of certain essential nutrients, or presence of toxic substances

The unfavorable properties of the soil are often amplified by inadequate scalping, too deep plowing, or careless planting. In some instances the trees are damaged by inundation, water or wind erosion, toxic industrial fumes, grazing, competition of grass vegetation, rodents, insect pests, or parasitic fungi. The deterioration of direct seedings may be caused by lack of mycorrhizal fungi.

If no adverse factors are revealed in field examination, information must be obtained on climatic conditions during the preceding few years, especially the occurrence of drought, winter killing, early and late frosts, evaporating winds, and temperatures high enough to cause sunscald. These data should be supplemented by a careful investigation of the origin of planting stock, particularly the source of seed, the content and balance of nutrients in the nursery soil, the method of nursery soil watering, shading, and fertilization, and the use of toxic fungicides, insecticides, and herbicides. In doubtful cases the advice of a plant pathologist or entomologist is highly desirable. The soil supporting the plantation should be subjected to laboratory analysis, provided that careful preliminary investigation has reasonably eliminated the possibility of non-edaphic causes of the deterioration. No conclusions should be reported unless they are based on positive evidence.

SURVEY OF FOREST PLANTATIONS

Periodic estimates of the rate of growth, quality of wood, and general vigor of established plantations on different soils are essential in all well-managed forests. As a rule, such periodic appraisals aid substantially in a more careful selection of sites for future reforestation because regularly spaced trees in plantations express much better the productive potential of soils than do natural forest stands of erratic life history and variable density. Moreover, the determination of the plantations' increment permits a closer estimate of the allowable annual cut on a sustained yield basis. At times, survey of plantations helps to reveal the incidence of diseases and insect injuries (Rudolf, 1950; Leaf and Keller, 1956).

Determination of the homogeneity of plantation areas. In order to draw definite conclusions on the relation of soil and tree growth, the surveyed plantation must first be checked as to its ecological uniformity. During a preliminary general examination, the soil is sampled at random by means of a tube or an auger, and an estimate is made of the size of the area and the number of trees per acre. If no deviations are observed, two parallel chain transects are laid out by the use of a compass at an angle with the direction of the rows, preferably along the diagonal of the plantation area. If the plantation is on a slope or a land of rolling topography, transects are laid out to cover topographical variations.

In young plantations, with trees whose heights do not exceed 25 feet, the trees are measured along the transects by a marked extendable aluminum pole. In older plantations, the heights are measured with a hypsometer or, in the case of a close spacing, the measurement of diameters is substituted for measurements of heights. In either case the measurements are made at a predetermined distance, for example, every fifth or tenth tree. The measurements should accumulate a sufficient population of data, assuring statistical significance of average values. Depending on the size of the plantation area and the height or diameter amplitude, the number of measured trees usually varies from 0.5 to 2.0 per cent of the total number of trees.

The uniformity of the plantation growth is checked by comparison of average values obtained on two parallel transects, as well as those on transect fractions. The relation of the standard deviation to standard error, coefficient of variability, and the standard error of the difference are calculated to determine the statistical significance of the results (Bruce and Schumacher, 1950).

Mensuration analyses. In young plantations it is sufficient to select three to five sample trees of average heights to be subjected to stem analysis. Average heights are used, since the expression of dominance does not take place in the absence of competition. In older plantations, especially those in which the height determination has been omitted, it is necessary to establish $\frac{1}{10}$- or $\frac{1}{5}$-acre sample plots. These plots are located in the regions of the transects characterized by the predominance of average values. The determination of heights and other elements of plantation growth on these plots is made according to standard methods (Chapman and Meyer, 1949). Then three to five sample trees of average height and diameter are selected for stem analysis.

In stem analyses the recorded data of length and diameter of sample trees are plotted against the age on graph paper. The results are graphically interpolated and a diagram of the rate of growth is constructed. This diagram presents a picture of the plantation development and allows the comparison of plantations of different ages.

If desirable, $\frac{1}{2}$-inch-thick samples containing from 7 to 9 annual rings are cut from the stem sections for the determination of the specific gravity of the wood (Spurr and Hsiung, 1954).

Analyses of the soil. The analysis of the soil is performed partly in the field and partly in the laboratory. Trenches are dug on representative portions of the area to a depth of 4 to 5 feet. The genetic nature of the soil is identified and a sketch of the soil profile and distribution of the roots is prepared. Particular attention is paid to the occurrence of porous, impervious, and mottled layers. Depending on conditions, the examination of the soil profile may be supplemented by field determinations of soil reaction, content of carbonates, soil texture, and permeability of soil layers to the passage of air.

In some instances the rate of plantation growth is radically modified by the influence of ground water, especially that charged with oxygen and electrolytes. Occasionally ground water found in coarse siliceous soils has high fertilizing effects because of its previous passage over base-enriched geological strata, lenses of lacustrine clays, and various intrusions in glacial deposits. Therefore, the analysis of hydromorphic soils should include a determination of the degree of oxygenation and hardness of the ground water.

Upon completion of the profile study, samples of the 6-inch surface soil, including the surface litter, are collected by means of a sampling tube. This layer, enriched in organic matter, usually contains the bulk of available nutrients; it serves as the storehouse of nutrients extracted by the root systems from deep layers of the soil and returned in the form of forest litter. The roots of young trees obtain a predominant share of their nutrients from this surface layer. If the lower layers of the soil, as revealed by profile examination, are of particular importance in the growth of trees, samples should be collected from these layers (Wehrli, 1956). In all instances when samples are collected for the determination of plant nutrients, care should be taken to determine the bulk density of the sampled soil layers.

The laboratory analyses are usually confined to the following characteristics: soil reaction, texture, content of organic matter, base exchange capacity, specific conductance, and content of available nutrients, particularly phosphorus, potassium, calcium, and magnesium. In special cases it may be necessary to include additional determinations.

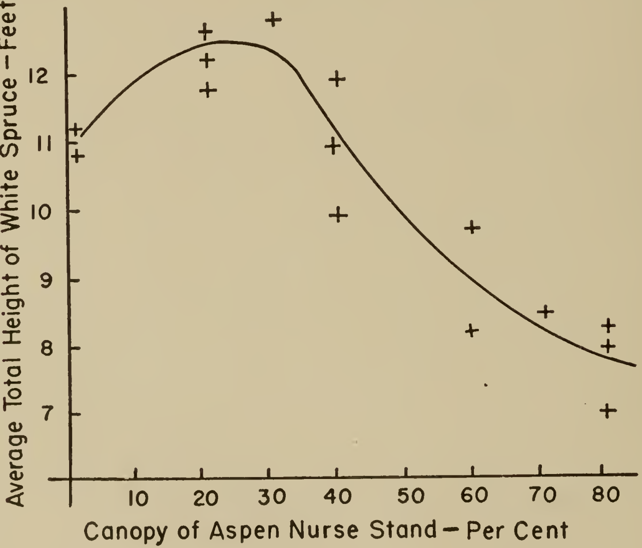


Fig. 15–5. Relation of the height growth of 16-year-old plantations of white spruce, supported by podzolic loams, and the density of nurse stands of trembling aspen, 40 years old. (From Leaf and Keller, 1956.)

It is of extreme importance in surveying plantations of tolerant species, established under the protection of a nurse stand, to make a careful estimate of the density of the overhead canopy. Figure 15–5 shows the relationship between the average height of 16-year-old white spruce plantations, supported by podzolized morainic loams, and the density of nurse stands of trembling aspen about 40 years old (Leaf and Keller, 1956).

SOILS AND FOREST TREE BREEDING

The reforestation program of all progressive-minded countries is now profoundly influenced by the search for better genetical varieties of trees and hybrids possessing a high growth potential and other desirable features.

Forest-tree breeding was fortunate to acquire from its parent disciplines the theoretical foundations of genetics and the practical knowledge of selection and hybridization techniques. Already feats have been accomplished in this field that have roused the admiration of plant specialists. It is sufficient to mention hybrid poplars producing a harvest of pulpwood at the infantile age of 15 years. Yet in spite of these successes forest-tree breeding, like many "child prodigies," is not free from the danger of a delayed or even an arrested maturity.

A sound development in any realm of life is the outcome of the nature as well as the nurture of specimens, a close correlation of the inherited growth potential with suitable environmental conditions. Therefore, the success of the propagation of superior tree strains is intimately bound to productive capacity of the soil.

The first problem of forest genetics in which soil fertility attains importance is the selection of superior, so-called "plus" trees to serve as a source of seed or breeding material. As a general policy, in such selections it is advisable to avoid too great differences in the composition of soils supporting parent trees and soils to be reforested. The origin of the soil, textural and structural properties of the soil profile, position of the ground water table, pH value of the soil, content of carbonates, and supply of essential nutrients appear to be among the characteristics to receive particular attention. In reforestation of sites subject to drought or winter kill, selected or hybrid stock should not be originated from the fast-growing elite parent trees developed under optimum ecological conditions. Such stock, with its hereditary high rate of growth, may be the least capable of surviving under conditions of either summer or winter deficiency of water. In securing planting stock for lands where frost injury may be expected, attention should be given to trees growing on gley soils of lowlands. In the regions of low temperatures, stands on such soils are exposed to severe frost damages. Therefore, as a consequence of natural selection, late-flowering varieties are developed, which are more resistant to spring frosts.

In the initial stages of a selection program it should be remembered that genetically inferior trees growing on fertile soils may have a much better appearance than genetically superior trees growing on soils of low fertility (Righter, 1932). Therefore, the choice of plus trees, or potentially elite trees, for breeding cannot be accomplished most efficiently without an appraisal of the soil productive capacity.

In certain geological formations, for example, in terminal moraines, the composition of the soil profile often changes within short distances, and the determination of soil influences may at times require many profile excavations. The local modifications in the soil productivity may be caused by the occurrence of a perched water table; irregular extensions of the capillary fringe; seepage; pockets of sand, clay, or lime; cementation or compaction of soil; or protrusion of rock substrata.

The genetic quality of the selected phenotypically superior trees is determined by planting their seed, grafts, and cuttings on testing areas and observing the growth of progeny or clones. This basically sound procedure may provide a totally misleading answer if trials are not conducted on a soil with a balanced and uniform fertility. The local variation in soil fertility may enhance the growth of inferior progeny and depress the growth of superior progeny. A deficiency of certain nutrient elements will render the trials meaningless.

Everything considered, it is best to conduct progeny tests on recently cleared forest land whose soil satisfies the requirements of species being investigated. The uniformity of the soil on such a proving ground should be carefully checked by field examination and by analyses.

If suitable recently cleared soils are inaccessible, fertility of the soil selected for progeny tests should be adjusted by available procedures. Such an adjustment may not duplicate the composition of the virgin soils in all details, but, as nursery experiences have demonstrated, it will make possible normal and uniform development of the tested progeny.

The superior offsprings, developed through progeny tests and controlled pollination, are planted in orchards to serve as a source of seed. Even though soil conditions cannot influence the hereditary characteristics of these genetically superior trees, unfavorable physical properties of the soil and unbalanced fertility will hinder the production of seed and may even lead to the deterioration of valuable clones. Therefore, the soils of seed orchards require the same careful attention as those of the progeny testing areas.

The arboreta are established to provide material of native and exotic tree species and varieties for breeding purposes. The value of such arboreta depends not only on the survival of the assembled forms, but also on their flowering capacity. Since different tree species, such as pine and spruce, have vastly different soil requirements, a genetical arboretum must consist of either a number of areas of suitable soils, or a section of land including a wide range of soil types. The care devoted to the selection of the right kind of soils will greatly facilitate the establishment and performance, especially flowering, of breeding material. The need for a periodic adjustment of soil fertility or other soil-improving measures in genetical arboreta is not excluded.

The achievements of agronomists and horticulturists in plant breeding suggest that this field offers a possibility of similar improvements in silvicultural crops. This may be particularly true when the program of tree breeding stresses the improvement of the form of trees or their resistance to climatic extremes and harmful organisms (Riker *et al.*, 1943; U.S.F.S., 1948). On the other hand, production of tree hybrids for the sole purpose of achieving exceptionally high yields is likely to present many difficulties. As a general rule, an inherently high rate of growth calls for a higher supply of available water and amplifies the vulnerability of trees to drought, frost, and winter kill; rapidly growing trees are less resistant to wind, sleet, and snow press. Thus, in certain respects, aims of tree breeding may sharply conflict with silvicultural philosophy which stresses the vigor of artificially created forests. The negative results may be eliminated or at least greatly reduced by a careful evaluation of site requirements of parent trees and selection of ecologically suitable breeding stock. In turn this may facilitate the production of hybrids better equipped to meet the rigid requirements of cut-over lands.

The development of the hybrids may attain certain improvements if the stock vigor is systematically evaluated by analytical methods devised by Langlet (1936), Meuli and Shirley (1937), and many agricultural breeders. A comprehensive bibliography dealing with the immunity and general vigor of originated strains, as well as the appraisal of these characteristics, is assembled in the English edition of Vavilov's book (1951). As suggested by Mirov (1937), physiological analyses may be of help in the determination of the ecological characteristics of parent trees and may facilitate the development of genotypes suitable to a given set of climatic and soil conditions. Physiological grading of nursery stock was emphasized by Wakeley (1951), and the technique of physiological analysis of tree seedlings was reported by Wilde and Voigt (1955).

Trees with their mycorrhizal symbionts have an enormous capacity for utilization of water and nutrients; some tree species produce high yields on rock outcrops by utilizing water of condensation and nutrients from unweathered minerals. Yet, like any other organism, trees cannot cope with a critical deficiency of either water or nutrients, and silviculture has shown in the past beyond any doubt that success of reforestation depends upon selection of suitable planting sites. These experiences were gained with planting stock of an average growth potential. The use of stock of a high growth potential, originated through selection or breeding, will considerably raise the standards in the choice of soils suitable for tree planting. In this regard there is no difference between forest and farm crops, and as correctly stated by Albrecht (1953), "One thing is sure—greater yields require greater quantities of plant food. The farmer switching to improved high-yielding varieties must of necessity use more fertilizer to gain the maximum advantage of the hereditary potential of the new strain."

Thus the utilization of the hereditary vigor of trees will require soils with an increased content of mineral colloids, organic matter, and nutrients; very likely it will impose more restricted ranges of soil reaction, a factor which influences the availability of nutrients; and it will demand greater permeability of soils, water-holding capacity, and aeration.

Therefore, unless the reforestation program is ready to provide soils of a reasonable fertility, rapidly growing varieties are likely to suffer losses from drought and frost, and the area of struggling nonmerchantable plantations that may serve as breeding centers for parasites will be increased.

These are the reasons why enormous areas of land now in need of tree planting will not be suitable for reforestation with rapidly growing varieties of trees. Such lands include coarse siliceous sandy soils, moisture-deficient soils of the prairie-forest and desert-forest transitions, soils depleted by repeated fires and prolonged cultivation or grazing, and podzolized soils of lateritic substrata, impoverished in nutrients by abundant rainfall and man's mistreatment. On all such lands, the genetically superior nursery stock may become ecologically inferior planting material.

Perhaps in some instances the use of rapidly growing strains on infertile soils will be possible with the help of artificial fertilization. As a rule, however, such practice will have to be confined to soils underlain by a ground water, soils influenced by an extended capillary fringe, and soils of humid regions, for example, those of the Atlantic Coastal Plain. Attempts to force the growth of trees by application of mineral fertilizers on soils deficient in moisture will only speed the destruction of plantations by drought or frost.

We came to a plain whose soil repels all roots.
—Dante, *Inferno,* Canto 14

16

Unproductive forest soils and methods of their improvement

The land: its assets and liabilities. The ownership of land is not only a privilege but also a financial responsibility. This is especially true of forest lands subjected to artificial reforestation or natural regeneration by partial cuttings, for both of these endeavors carry an element of uncertainty. Regardless of its origin, a young forest stand represents an investment and its financial return depends upon the rate of the stand's growth. When the current increment drops below a certain level, the forest stand becomes a liability rather than an asset; it consumes the interest on the invested capital as well as tax money and current expenses. This unsound financial condition, often encountered in forestry practice, can be remedied only by the assignment of the land to a different form of utilization or by amelioration of soil conditions. This chapter summarizes methods of soil improvement which are within the reach of a forest manager.

UTILIZATION OF RUN-OFF WATER

In numerous instances water is the factor which limits the productive capacity of forest soils. In regions with undulating or rolling topography this deficiency may be partly corrected by interception and careful distribution of run-off water through a network of shallow ditches or plowed furrows (Fig. 16–1). The furrows are laid out perpendicular to the main drainage channels, with a gradient not exceeding 1 per cent. If the soil is predisposed to erosion the allowable gradient may be even lower. The water from the drainage channels is diverted from its course by furrows and is gradually absorbed by the soil. Simple dams of cull logs or poles are constructed in the main drainage channels to facilitate the diversion of water into the furrows (Fig. 16–2). The system of intercepting ditches may conserve as much as 30 per cent of the total precipitation water which is otherwise lost in the form of surface runoff. Work of this kind provides useful employment for permanent forest labor in slack seasons.

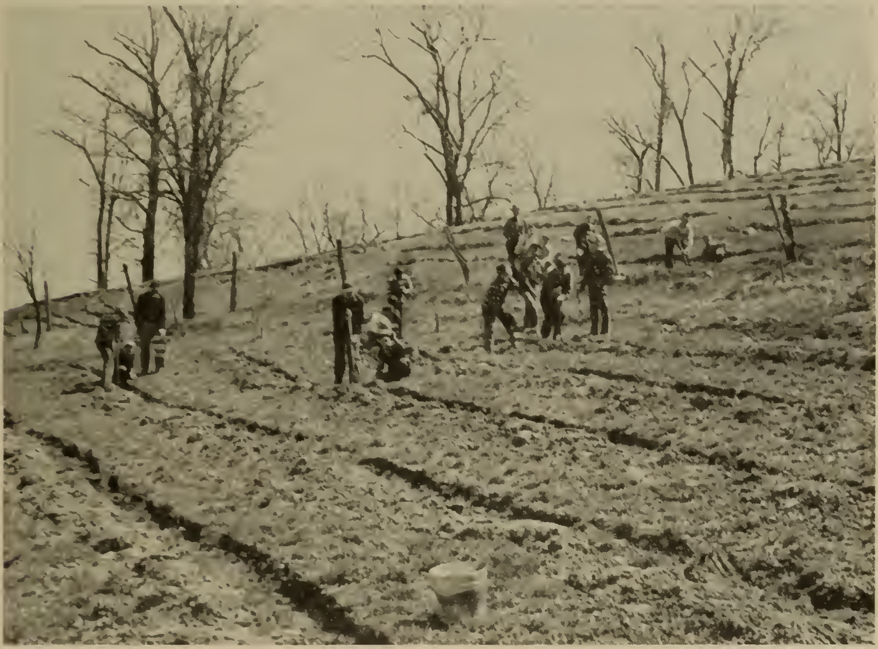


FIG. 16–1. Reforestation of a hillside by the use of contour furrows. (Wisconsin Conservation Department.)

Sometimes the construction of intercepting ditches is made for the double purpose of conserving moisture and encouraging natural forest reproduction, whose establishment is facilitated by the exposed soil of furrows and furrow slices. If desirable, this process is encouraged by application of lime and fertilizers.

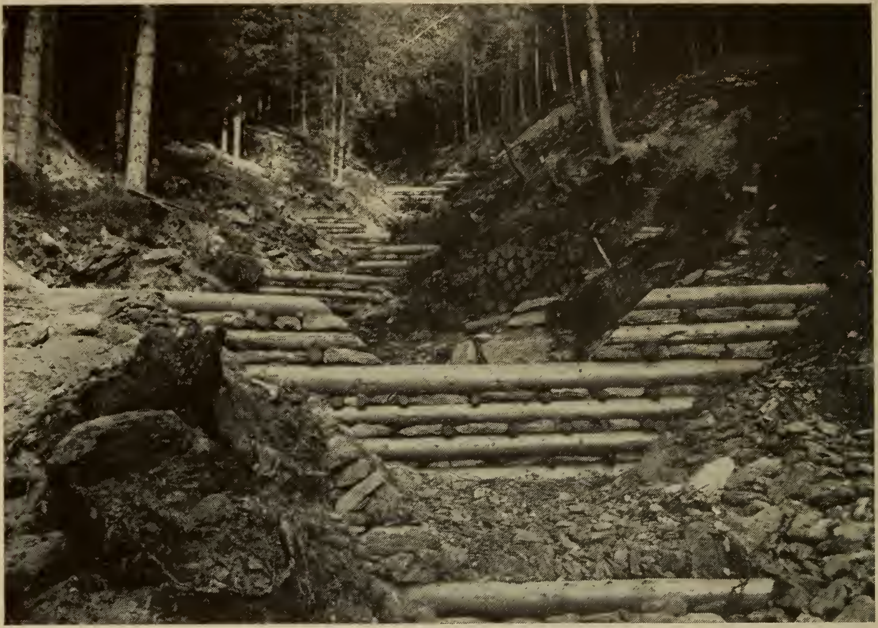


FIG. 16–2. Dams constructed of logs and stones to moderate the runoff in channels of steep gradient or to divert water into interception ditches.

CONSTRUCTION OF ARTIFICIAL WATER BASINS

In regions of not too productive soils and suitable topographic features, consideration may be given to the damming of streams and the creation of artificial lakes and flowages. Chief benefits of such water reservoirs include the reduction of fire hazard, conservation of melt waters, a slight increase of the air humidity in the adjacent territory, and enlargement of the habitat for fish, waterfowl, and fur-bearing animals. In regions of plains and terraces the damming of the stream may bring the ground water table to a suitable height to benefit the growth of forest stands on the bordering uplands. Such an improvement, however, may be partly or wholly offset by a simultaneous deterioration of lowland soils located within the influence of the backwater.

DRAINAGE OF WET LANDS

The artificial lowering of a high ground water table may be, under certain circumstances, a feasible means of stimulating forest growth. The drainage of small areas underlain by a thin impervious layer can be improved by dynamiting or digging holes which facilitate the "sinking" of the excessive water. A special auger with extensions is advantageously employed for this purpose. In some cases it may be necessary to install a vertical tile which comes within 3 feet of the ground surface. Stream improvement aiming at accelerating the current, especially the removal of beaver dams, may materially decrease stagnation in backwater swamps and marshes. Frequently a short outlet ditch is sufficient to penetrate a barrier which is responsible for the retention of run-off water. The drainage of ravines choked with fallen logs may be easily accelerated by merely clearing the rubbish from the surface. Inexpensive intercepting ditches may be installed to keep the surface and seepage water from entering potholes. By these methods the amelioration of impeded drainage may be accomplished with very little expense. As a rule, minor drainage improvements are confined to areas supporting stands or plantations of valuable species and are carried on by permanent forest labor during slack work periods.

The drainage of large areas, particularly swamps, requires investigation of a number of conditions previous to the initiation of the project proper. The following aspects are of particular importance: (1) the potential productivity of the soil or peat; (2) the practicability and efficiency of the proposed drainage system; (3) the expected financial return on the investment; (4) the effect of drainage and the subsequent lowering of the ground water table upon the productivity of surrounding upland stands; (5) the effect of drainage upon the entire water regime of the region, and especially its effect upon agriculture. In climates where drought is a serious problem, the two latter conditions usually make extensive drainage projects inadvisable.

The depth and permeability of the subsoil are examined by means of an auger or post-hole digger. The outlet is investigated with surveying instruments. The leveling should be continued some distance below the proposed outlet to make certain there is no danger of backwater. Specific literature on the subject and a technician experienced in drainage work should be consulted whenever an extensive project is contemplated (Zon and Averell, 1928; Ayres and Scoates, 1939).

The drainage of wet forested land, as a rule, is accomplished by open ditches (Fig. 16–3). The installation of tile drain is seldom practicable because of the tendency of tree roots to plug the pipes. If the area has no outlet, excess water may be removed by means of a so-called "Swedish drain." This consists of a continuous storage ditch which surrounds the basin area and intercepts the water from the higher portions of the topography. The general aim of drainage

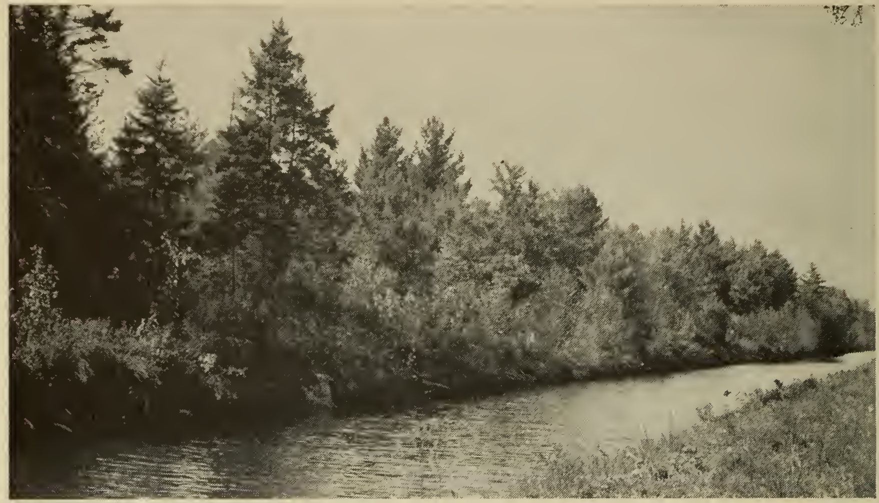


FIG. 16–3. Main drainage ditch serving to discharge water from poorly drained forest land.

for forestry purposes is to speed up the flow of the ground water rather than to attain a "bone-dry" condition (Averell and McGrew, 1929).

Because of the high cost, tree planting on peat lands is limited to rare cases. A reasonable assurance of success often requires an elaborate afforestation procedure. After the drained peat has settled to about two-thirds of its original volume and an invasion of grasses and sedges is evident, the soil from the drainage ditches is spread on the surface of the peat and the area is burned. The fire is set on the windward side so that it will move rapidly and not penetrate deeply. The burned-over area is then kept in buckwheat for about 5 years. In the fall of the sixth year the peat is disked, burned once more, and in the spring is planted to trees. Depending on the condition of ground water level, the seedlings are planted in slits or on top of the ridge formed by two furrows turned inward. Sometimes the surface layer of peat is removed by a power shovel before reforestation and is used as fuel or fertilizer material.

REGENERATION OF RAW HUMUS SOILS

In many places of central Europe the occurrence of raw humus is correlated with the retarded growth and gradual deterioration of pine and spruce stands. In some localities the accumulation of raw organic remains coincides with the development of a true podzol profile and cementation of the *B* horizon into stonelike hardpan; in other places raw humus is formed on soils which exhibit only traces of podzolization. The poor growth of trees has been attributed to the physical, chemical, and biological properties of these so-called "sick soils," and particular stress has been often placed on the presumably ill effects of the raw humus layer and of the cemented Ortstein horizon (Ramann, 1911; Weis, 1929; Mařan, 1938).

This problem, now occupying the attention of many European investigators, can be considerably narrowed by a review of American experiences. Raw humus layers of certain composition may handicap natural regeneration of forest stands; the hardpan may present an obstacle to tree planting or influence adversely the growth of young forest plantations. On the other hand, highly productive stands of both coniferous and deciduous species are found in the United States on soils covered with thick layers of matted raw humus and underlain by stonelike hardpans. Obviously, therefore, neither the physical makeup of the organic layer nor the presence of the hardpan horizon, as such, are responsible for the inadequate growth of trees.

In all probability, the decrease in the productive capacity of "sick soils" results from the arrested activity of saprophytic organisms and the interrupted release of nutrients. A condition of this kind can largely be caused by inadequate soil aeration or by a radical deficiency of some nutrient element. "Sick soils" observed by the author were invariably those subjected to previous agricultural use or derived from siliceous parent materials. The results of several studies indicate that the decomposition of raw humus may be stimulated by application of lime and nitrogen fertilizers or basic slag carrying calcium and phosphorus (Jacks, 1954). Undoubtedly, the limiting factor may also be potassium, magnesium, boron, and other trace elements.

Therefore, the road toward regeneration of inert or "pathological" forms of humus is likely to lead through Neubauer tests for available nutrients and trials employing application of fertilizers. Unless the existing deficiency of mineral elements is corrected by suitable treatment, the scarification of the ground, cultivation of legumes, and underplanting of soil-improving trees and shrubs will not ameliorate growth conditions. Especially careful investigations of soil deficiencies must be accomplished before the stagnating stand is removed and an effort is made to rejuvenate the hardpan podzol soil by deep plowing, dynamiting, and other costly radical methods.

RECLAMATION OF HARDPAN SOILS

The extensive areas of hardpan podzols, or "Heide," supporting low shrubs of the heather family, are ameliorated by deep cultivation by use of a steam plow. The cultivation is often preceded by burning the vegetative cover. The land is plowed to a depth of approximately 18 inches or deeper; the plowing is repeated in crosswise manner until the hardpan material, leached soil, and raw humus are thoroughly mixed. Sometimes the hardpan layer is destroyed by dynamiting instead of plowing. As a rule, lime or marl is added to decrease the acidity of soil, speed up nitrification, and convert into available form the nutrients concentrated in the hardpan layer. After cultivation the land is fallowed for one or two years or is seeded to green manure crops, particularly to lupine (Meinecke, 1927). This technique of soil reclamation was originated largely in northern Germany, Jutland, and Holland.

Pine and spruce are the chief species used for reforestation, the choice being dependent upon the texture of soil and other conditions. White birch, aspen, oak, hornbeam, mugho pine, and larch are planted with spruce and pine for the purpose of soil improvement. American red maple, which grows naturally on podzol soils, may be of great value as an associate species in this type of reforestation. The seedlings are usually planted on the top of the ridge formed by two inward-turned furrow slices.

Before the amelioration of a hardpan podzol is attempted the composition of the soil profile should be carefully investigated over the entire area. Since the depth of the Ortstein layer varies considerably from place to place, there may be many areas which have a sufficiently deep leached layer to allow direct planting. Plowing is likely to be most advantageous on areas with a shallow and thin cemented layer which may be completely destroyed by the plow. Experience has shown that the furrowing of thin hardpan soils results in the increased growth of planted seedlings due to the benefit of the additional nutrients from the disintegrated hardpan material. In places, neither direct planting nor plowing are practicable, and the area should be left to natural reproduction.

The amelioration of forested hardpan soils is carried on over a long period of time by means of partial cuttings which discourage the accumulation of raw humus, and by underseeding or underplanting of soil-improving hardwood species (Emeis, 1875; Wiedemann, 1923; Mařan, 1938). In many instances broadcast applications of lime and nitrogen fertilizers were also found beneficial.

STABILIZATION OF BLOW SANDS

The stabilization of sand dunes was one of the earliest activities of foresters in both the Old and New Worlds. In European countries attempts to bridle moving sands date back to the middle of the eighteenth century (Gehrhardt, 1900). In America, dune fixation at Cape Cod was initiated in 1826 (Backer, 1906). A graphic description of the destructive effect of wind erosion is given by Kroodsma (1937):

> To a person unfamiliar with moving sand dunes, it is hard to realize their magnitude or the grim wave-like action with which they advance, burying everything in their path. Examples of their destructive action are numerous. Old geographies of Michigan show that a once thriving sawmill town was located at the mouth of the Kalamazoo River near the present town of Saugatuck. Singapore was completely buried by a sand wave and became known as the Pompeii of America . . . In other sections of the state, highways are being covered, harbors are filling up and resort cottages are threatened with burial. [Fig. 16–4.]

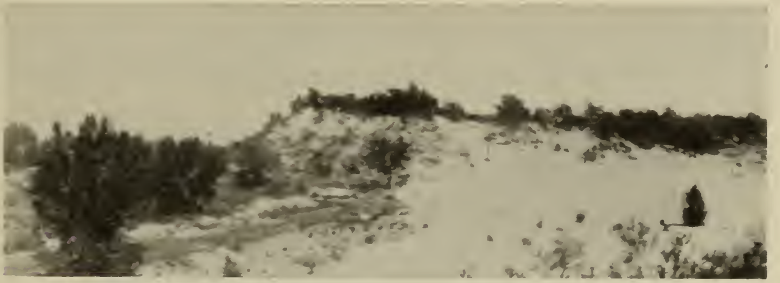


FIG. 16–4. The "grim wave-like" advance of aeolian sand along the eastern shore of Lake Michigan, an act of nature demonstrating in a dramatic fashion the importance of vegetative cover and soil colloids.

In only a few instances can the movement of sand dunes be arrested by direct planting of trees. As a rule, the blow sands must be at least partly stabilized prior to tree planting. This may be accomplished by means of wooden stakes which are cut to a length of approximately 20 inches and driven into the ground to a depth of 8 inches to form a series of fences. The fences are arranged in parallel rows or in the form of squares or rhomboids. The distance between the rows varies with the intensity of erosion and is determined on the basis of experience. The determination of the proper distance between the rows is of extreme importance, as it regulates the efficiency and cost of control (Heusohn, 1929). The spreading of slash, cornstalks, hay, reeds, or any other suitable materials on the windward side may replace the expensive construction of fences. The planting of xerophytic grasses in clumps or the sowing of rye is another method of sand stabilization. *Elymus arenarius* and *Ammophila arenaria* are the grass species commonly used. The latter is particularly favored in the United States (Lehotsky, 1941).

After the sand movement is arrested, the dunes are planted to jack pine, Virginia pine, pitch pine, Scotch pine, Austrian pine, ponderosa pine, mugho pine, maritime pine, Russian willow, cottonwood, or black locust. In exceptionally humid regions near the sea or large lakes, more exacting species, such as white pine, red pine, birch, white poplar, and European gray alder, are planted in the depressions between the dunes. In most cases, conifers proved to be superior to deciduous trees. Experience has shown that the control of sand movement is best achieved by a combination of several control measures, such as spreading brush, tree planting, and seeding of grass.

AFFORESTATION OF ROCK BARRENS

The processes of erosion in places remove the entire mantle of weathered fine-earth and expose the bedrock (Fig. 16–5). This is especially common in regions of calcareous formations, as exemplified by the ill-famed Karst Mountains (Leiningen, 1931). Restoration of vegetative cover on such denuded areas is one of the most difficult tasks of land amelioration. Yet many astonishing conversions of rock outcrops and talus slopes into productive forest tracts

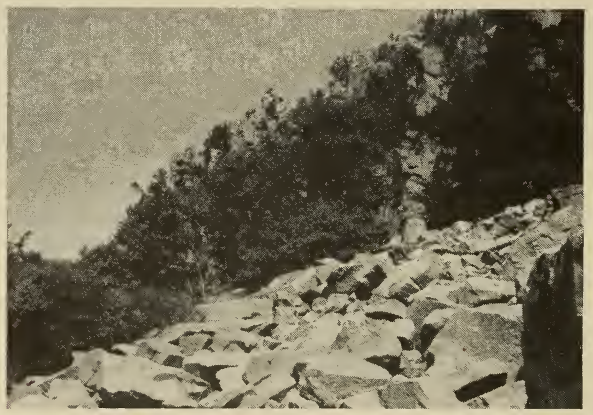


FIG. 16–5. Nearly vertical outcrops of sandstone and rock falls in the process of afforestation. (Wisconsin Conservation Department.)

have been accomplished by foresters of Austria, France, and other countries of central and southern Europe.

Many times, the afforestation of rock barrens is achieved by filling fissures or crevices with soil transported from nearby valleys. Sometimes trenches are excavated in the rocks to receive the soil and seedlings. In afforestation of barren slopes of the Apennines, the Italians construct a series of low stone walls to retain the soil in which the seedlings are planted. The cost of planting may be as high as $120 per acre. Under American conditions, this expense may be justified only in cases where rock falls threaten lines of communication.

Afforestation is usually initiated with Austrian or Corsican pine, other pines, larch, red cedar, black locust, European gray alder, and other pioneer species of trees and shrubs (Dengler, 1930). In planting on calcareous rocks, the selection must be limited to species tolerating alkaline reaction and a high content of carbonates. In time, the pioneer plantations may be reinforced by the underplanting or underseeding of hardwoods endowed with vigorous root systems.

CONTROL OF GULLIES

Gullies are usually the end result of various forms of land abuse. In the early stages, the destructive effects of runoff may be arrested by limited reforestation, simple dams of culled logs, and similar inexpensive measures. The progress of gully erosion proceeds at an extremely rapid rate, and in the course of a few years its control may present a serious problem for both foresters and engineers (Bennett, 1939).

Species used in planting gullies and surrounding territory are chosen chiefly on the basis of their ability to control erosion. Each gully includes three sets of ecological conditions: bottom, which periodically receives a considerable quantity of run-off water; eroded slopes with "raw," humusless soil; bordering banks with a normal soil profile, undisturbed by erosion (Fig. 16–6).

The slopes and the drier bottoms are planted to black locust or other drought-resistant trees with a fibrous, soil-binding root system. The wet gully bottoms are stabilized by moisture-loving trees, such as cottonwood and willows. The border strips are planted to a variety of trees and shrubs, including Russian olive, buffaloberry, Siberian pea tree, staghorn sumac, Russian mulberry, osage orange, privet, thornapple, thornless honey locust, highbush cranberry, nannyberry, common lilac, and wild plum. The selection of species

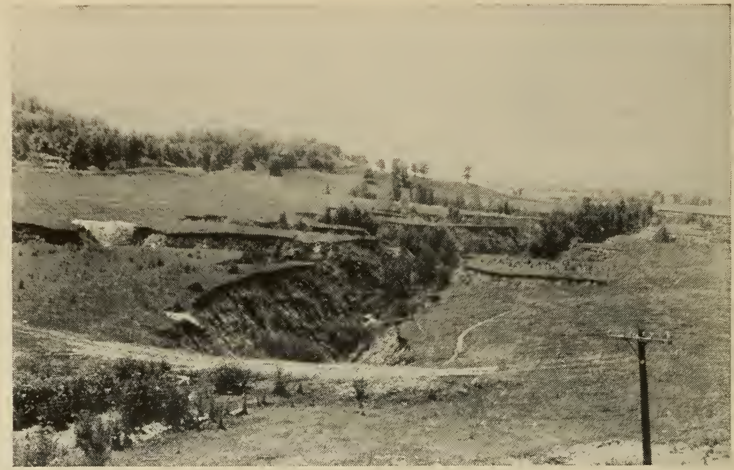


FIG. 16–6. Gully erosion partly arrested by trees. (Prof. O. R. Zeasman.)

depends upon climatic and soil conditions. On suitable soils, spruce, pine, and cedars are sometimes mixed with deciduous species to provide food and winter cover for game.

Because of the low fertility of the eroded portion and the heavy sod on the undisturbed slopes bordering the gully, only large stock is used. The spacing varies from 2 by 2 to 3 by 3 feet. In some instances tree planting is supplemented by the seeding of eroded banks to timothy, rye, bluegrass, and clover, or by sodding exposed sections. Extensive gullies may require engineering work prior to reforestation (Fig. 16–7).

RECLAMATION OF SPOIL BANKS AND INDUSTRIAL WASTE BEDS

Few pictures of destruction brought about by modern warfare can compare with the sinister landscape of many square miles on which strip mining utterly distorted the "face of the earth." Because there is no rapid method of plastic surgery to heal the scars caused by monster-like cranes and bulldozers, the rehabilitation of waste beds and spoil banks is a slow and costly process.

In many instances, before afforestation, the man-made "badlands" must be stabilized by erosion control structures, grading of steep slopes, partial resurfacing with fertile soil, mulching, and spreading of slash. The technique of amelioration varies widely, depending on the composition of the regolith, and rehabilitation must be preceded by careful physical and chemical analyses of geologic debris. Particular attention should be given to the texture of the exposed

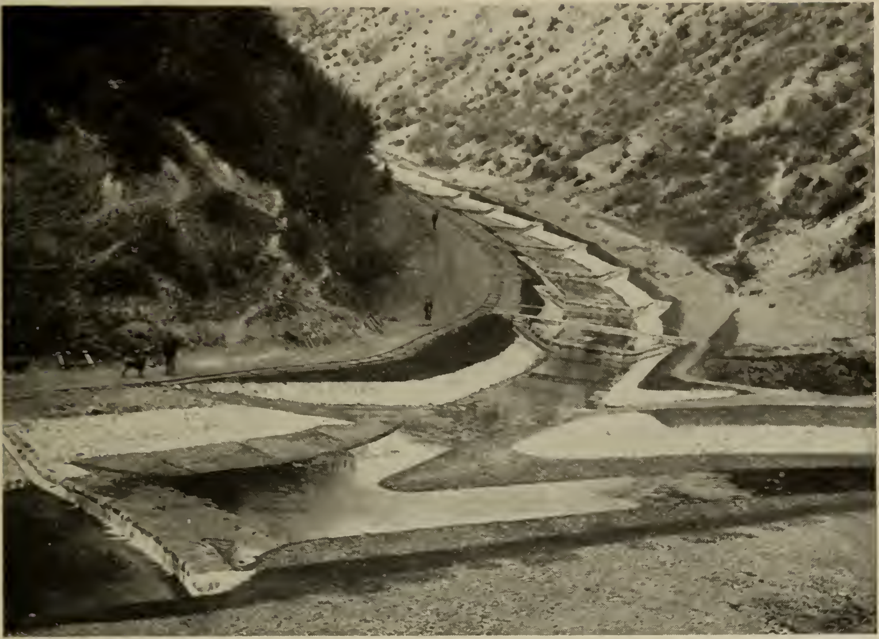


FIG. 16–7. An example of combined engineering and reforestation measures for the stabilization of an extensive gully in Austria. (V. Kaisler.)

substratum, its permeability to air and water, aeration at field capacity, reaction, content of carbonates, supply of available mineral nutrients, specific conductance, and the content of toxic substances.

Because of the deficiency of organic matter in the soil, wide use should be made of trees and shrubs which have the ability to fix atmospheric nitrogen, particularly black locust, European gray alder, and Scotch broom. These may be supplemented by the least exacting pioneer species, for example, Virginia pine, jack pine, pitch pine, Austrian pine, juniper, eastern red cedar, hawthorn, Tartarian honeysuckle, and lilac. The depressions or kettle holes, which accumulate run-off water, are best suited to willows, poplars, and alders.

If the gradient and nature of the substratum permit, attempts should be made to plant trees in furrows plowed on contour lines. In spite of all precautions, the plantation may suffer from overwash of eroded material, and sodding or seeding of cover crops may be imperative on certain areas. On debris deficient in nutrients, the establishment of legumes or grasses may require application of fertilizers. Planting stock on fine-textured material may be damaged by frost heaving. Some industrial waste beds may contain toxic substances or soluble salts in a concentration injurious to plants. On such sites the use of halophytic trees and shrubs such as desert willow, Kirghisian birch, saksaul (*Haloxylon ammodendron*), tree of heaven, and honey locust may be necessary.

AFFORESTATION OF PRAIRIE SOILS

The first efforts to afforest prairie lands were based on the assumption that planted forests will increase the amount of rainfall and thus will benefit the climate in the entire region. Although these ideas have recently proved unfounded (Mirov, 1935), there are other reasons which justify "prairie forestry." In no other region have shelter belts, windbreaks, or farm woodlots such value as in vast grasslands; plantations of this kind protect dwellings and livestock, and provide wood for fuel and general use. Paradoxically, tree planting in prairie regions often has much greater social and economic importance than tree planting in forest regions. Marquis James, in his book *The Cherokee Strip,* gives a vivid picture of the role which trees play in the grassland region:

> We had the boon of natural shade, the Big Tree being the claim's crowning glory. Reared under its branches, I would not appreciate the fuss people made over trees . . . I have heard tell that people sometimes went mad on dry claims with nothing to hear but the ceaseless prairie wind and nothing to see but the bending grass of the featureless plains.

Climatic conditions of prairie lands are characterized by low annual precipitation, temperature extremes, periodic droughts, delayed snowfall, and frequent severe winds which remove the protective snow cover. The soils include chernozems, chestnut soils, white and black alkali soils, and areas of dune sands. The areas comparatively best suited for tree planting in this forest-hostile environment are confined to slopes which collect snow drifts and thus ensure a higher content of soil moisture. On such sites the percolating water lowers the zone of lime enrichment and decreases the concentration of soluble salts. Alkali soils of depressions, enriched in soluble salts, and soils with a zone of lime enrichment close to the surface are the least favorable to the growth of trees (Scholz, 1935).

The afforestation of prairie is often initiated by planting shrubs and dwarf trees which help to accumulate snowdrifts and thus promote the process of salt removal. After leaching has decreased the pH value of the surface soil and lowered the zone of lime enrichment, the area may be planted to more valuable trees (Buchholz, 1930).

The survival and growth of trees in grassland regions are often better on sandy soils than on clay soils because of the higher content of available water in sandy soils. The content of available water in clay soils is greatly reduced by a slow absorption rate, surface runoff, retention of light precipitation in the upper soil layer, and a high wilting coefficient. Large cracks, fracturing clay soils in drought periods, cause excessive drainage by channeling water and otherwise handicap the growth of trees (Stoeckeler and Bates, 1939).

The tree species which have proven most successful for prairie planting are green ash, hackberry, American elm, Chinese elm, bur oak, black locust, honey locust, catalpa, osage orange, willows, cottonwood, ponderosa pine, Austrian pine, Colorado blue spruce, junipers, and eastern red cedar. The shrub species commonly used include Russian olive, buffaloberry, chokecherry, Siberian pea tree, serviceberry, hawthorn, Russian mulberry, Tartarian honeysuckle, nannyberry, and lilac (Silcox *et al.*, 1935).

Recent evidence indicates that an inoculation of seed with mycorrhizal fungi is essential in the afforestation of prairie soils (Hatch, 1936; McComb, 1938; White, 1941; Rosendahl, 1943).

The areas to be planted are often fallowed to reduce the competition of grasses and to increase the content of soil moisture. In some instances, the planted areas are periodically cultivated for the same purpose.

USE OF FIELD CROPS IN REFORESTATION

On soils possessing a reasonably high content of nutrients, rye, oats, or other cover crops are sown sparingly at the time of the tree planting. In the fall the cover crop is cut high with a scythe or mowing machine. This practice provides some protection to seedlings during the first growing season. Income from the sale of the harvested grain may help to defray the cost of planting. Potatoes and corn are raised between rows of planted trees for the same purposes. Such combined use of the land, however, is often detrimental to forest plantations, especially on soils poor in nutrients or soils with unstable structure.

CULTIVATION OF FOREST STANDS

The stagnant growth of plantations, caused by the competition of weeds, can be materially improved by cultivation. In reforestation of Wisconsin sandy podzols, repeated disking has increased the average height of jack pine on some areas from 3.9 feet to 11.2 feet in the course of nine years.

Cultivation is accomplished by means of a one-horse cultivator, special Neumann forest cultivator, disk, or rototiller. Great care must be exercised in cultivation to avoid injuring the tree roots. On soils deficient in humus, cultivation is likely to have detrimental results as it promotes the decomposition of organic matter and subsequent leaching of nutrients. Cultivation may also affect adversely the porosity and aeration of the surface soil (Burger, 1922).

Harrowing or raking is sometimes practiced on raw humus soils to stimulate natural regeneration of stands.

IMPROVEMENT OF SOIL FERTILITY BY UNDERPLANTING OF SOIL-CONSERVING SPECIES

The aim in underplanting soil-conserving species is to create an understory of trees or shrubs which accumulate in their leaves a high content of bases. The deposition of such litter tends to moderate acidity, increases the content of available nutrients, and subsequently improves the physical properties of soil.

This practice is confined primarily to sandy or strongly podzolized soils. Four deciduous species most commonly used are beech, oak, basswood, and hornbeam. Of these only the latter two appear to be entirely satisfactory; beech in some localities contributed to the accumulation of raw humus, and oak is too light-demanding to be used under a dense canopy. American maples, notably *Acer saccharum* and *A. rubrum,* may play an increasingly important part in silvicultural underplantings. The results obtained with underplanting black locust are contradictory, and the introduction of this tree requires caution. In some climatically restricted areas, European fir was found of considerable value as an understory in spruce stands.

In spite of significant improvements that have been sporadically achieved in underplanting of soil-conserving species, this practice is costly and not always successful, for the establishment of tolerant species on poor soils encounters difficulties. In regions deficient in moisture the understory may increase the competition for available water. The success of underplanting, therefore, depends on expert judgment, and discouraging results are to be expected.

BURNING THE FOREST FLOOR

Ground fire is an old practice in decreasing soil acidity and liberating readily available phosphorus and bases from organic remains. In the past, forest burning on a large scale has served the purposes of both farming and silviculture; it is still in wide use in northern European countries and on the Atlantic Coastal Plain of the United States.

Aside from the fire hazard, burning the forest floor is objectionable because it results in a total loss of the most valuable fertilizer ingredient, nitrogen. Moreover, the released bases may be rapidly lost by leaching in the absence of organic colloids. These ill effects of burning have been emphasized by many writers. In spite of this, the problem of the total influence of the ground fire under different climatic conditions is far from being solved. Several authorities, such as Rubner (1927) in Germany and Hesselman (1928) in Sweden, consider floor burning beneficial on strongly podzolized soils with a thick layer of raw humus. The wholly detrimental effect of fire is also denied by many foresters operating on lateritic soils of America (Heyward and Barnette, 1934).

USE OF FERTILIZERS FOR IMPROVEMENT OF FOREST STANDS AND PLANTATIONS

Commercial and natural fertilizers entered forest practice through two different channels: soils of nursery beds and soils of forest plantations or second-growth stands. The use of fertilizing materials in these two phases of silviculture has produced results of widely different significance. During the past two decades, foresters have made remarkable progress in artificial maintenance of fertility in their permanently cropped nursery soils; in this realm forestry has attained as high a level of efficiency as that found today in agronomy. In some instances the value of nursery crops, worth many thousands of dollars per acre, and the need for rigid control of soil fertility have helped foresters to achieve refinements unknown to farming. At the same time, the use of fertilizers for the encouragement of growth of artificially and naturally established forest stands presents problems that cannot be solved without additional research. The following review summarizes past experiences with the use of fertilizers in forest stands and plantations and outlines present possibilities for augmenting the fertility of forested soils.

Investigations of fertilizer influences on tree growth were initiated in the fifties of the past century. Since that time numerous fertilizer trials in forest plantations of Germany, Austria and Czechoslovakia have been conducted. In most trials, positive results were obtained with the use of green manure crops, particularly lupine, and with the application of organic remains, such as litter and slash. Considerable improvements in the growth of forest plantations due to application of lime and crushed rocks rich in bases have also been observed. The effect of soluble mineral fertilizers was irregular and often short-lasting. In many trials such fertilizers failed to exert any influence, or even depressed the growth of trees. In other cases applications of soluble salts stimulated the growth of stands established on soils worn out by previous farming use, as well as stands injured by drought, fire, and insects. The benefit of fertilizer treatments was more pronounced on soils possessing an adequate supply of water than on droughty sands. Hardwoods, on the whole, showed better response to fertilizer treatments than did conifers; pioneer species, particularly pines, responded the least. Detailed accounts of the results obtained during the initial stages of silvicultural research in fertilizers were given by Koderle (1865), Vater (1910), Schwappach (1916), Süchting (1929), Leiningen (1931), Wiedemann (1931), and Becker-Dillingen (1939).

The conflicting results of early fertilizer trials may be attributed to several causes, namely: (1) insufficient knowledge of soil chemistry, action of fertilizers, and nutrient requirements of tree species when the trials were initiated; (2) competition of weed vegetation which developed vigorously on the fertilized soil and deprived the trees of moisture; (3) occasional drought or winter kills which not only annulled the benefit of the fertilizer treatment but made such treatment harmful.

Until recent times, the interest in forest stand fertilization was confined to a small group of specialists concerned with forest soils. Silviculturists usually were inclined to disregard the nutrient content of soils and to accept whatever yield of timber was produced on an area of a definite "site quality." The latter unit of classification, arrived at on the basis of average height of dominant trees, for two centuries was regarded as a fixed constant determined by powers beyond man's control. The global war of the past decade radically changed the outlook of both forest professionals and owners of timber lands. The immense consumption, as well as destruction, of wood material during the war compelled foresters to search for new means of increasing timber production. This search became particularly urgent because the increment of many forest stands and plantations in this country and abroad failed to fulfill expectations. As a result, studies of nutrition of trees attained renewed vigor, and literature on using fertilizers in forest stands was enriched.

A remarkable increase of several hundred per cent in the volume growth of some red pine plantations was achieved in the state of New York by broadcast applications of potash fertilizer made after the plantation had closed its canopy (Heiberg and White, 1951). Improvement in the growth of pine plantations has also been observed in the same state with the use of stock grade Epsom salts on soils deficient in magnesium (Stone, 1953). Trials in the Pacific

Northwest demonstrated a response of Douglas fir to nitrogen fertilization (Gessel and Walker, 1956). Positive as well as negative results with the use of commercial fertilizers, composts, fertilizer briquettes, and green manure crops were obtained in Wisconsin trials (Wilde, Trenk, and Albert, 1942; Wilde and Wittenkamp, 1942; Wilde, 1956).

A spectacular stimulation of growth of Scotch pine and Corsican pine was achieved on certain soils of England by Rayner and Nielson-Jones (1944) through application of inoculated composts (Fig. 16–8). In the opinion of some English foresters, not based on exacting research, the fertility of all soils of the British Isles now available for reforestation is in need of correction by application of suitable fertilizers. According to Leyton (1954) the poor growth of trees

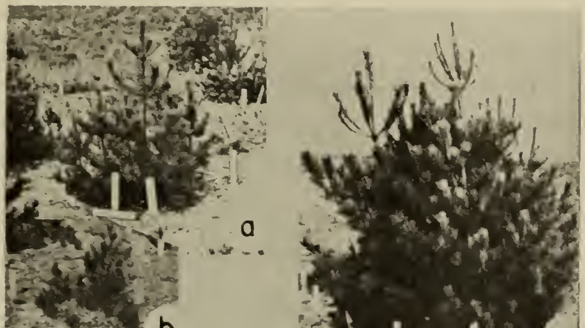


FIG. 16–8. Stimulation of growth of Corsican pine on Wareham experimental area, England, by application of mycorrhiza-inoculated composts: (*b* and *d*) unfertilized plots; (*a*, *c*, *e*, *f*) plots fertilized with various composts with and without inoculum of Corsican humus. (After Rayner and Neilson-Jones, 1944.)

on heath soils may be corrected either by application of nitrogen fertilizers or by the removal of heather and subsequent decomposition of roots remaining in the soil. The same author reported an improvement in the growth of trees by an addition of phosphate and potash fertilizers. On other soils of England, particularly on upland peats, the growth of conifers was promoted by dressing the seedlings with basic slag, a phosphate fertilizer containing lime (Jacks, 1954).

Two reports comprising 700 pages were published by Němec (1950 and 1956) on his long-duration fertilizer trials in a highly diversified environment of Czechoslovakia. These reports, augmented by more than 400 references, are among the most important of recent documents which may serve as the basis for further endeavors of foresters to increase timber production by the use of fertilizers.

In Germany, attempts are being made to use lime, commercial fertilizers, anhydrous ammonia, sewage sludge, and other waste products for the correction of nutrient deficiencies, rejuvenation of inert raw humus, and encouragement of natural reproduction. Reports covering recent achievements of German foresters with the use of fertilizers were published by Hausser and Schairer (1953), and Mayer-Krapoll (1956). In spite of many examples in which the use of fertilizers increased the growth of forest stands, Wittich (personal communication) suggests that a great deal of caution should be exercised in appraisal of the results obtained with experiments on small areas and of short duration.

The review of experiences in different parts of the silvicultural world suggests that fertilizing materials of one kind or another are becoming entrenched in forestry practice. Nevertheless, the success of fertilizer treatments of forest stands in certain cases does not mean that the large-scale use of fertilizers in silviculture is free from formidable problems. Some of these problems, particularly the economic soundness of treatments and mechanization of the application procedure, hold promise of comparatively easy solution. The most difficult task concerns the capacity of different soils to transmit the effects of fertilizer treatments to the growing stock. This capacity is the result of several conditions, including the supply of soil water, air and nutrients, the humidity of climate, and the length of growing season. The concept of **fertilizer responsiveness of soils** should be placed in the foreground of all forestry fertilization work and deserves elaboration.

If a species of high-moisture requirements, such as Norway spruce, is planted on a coarse sandy soil in the continental climate, application of fertilizers will serve no useful purpose, because on such sites the growth of trees is arrested by the deficiency of water not of nutrients. Similar negative results should be expected from application of fertilizers on some waterlogged soils that lack sufficient aeration; occasionally, addition of fertilizers to poorly drained soils may depress rather than improve the growth of forest stands. In soils which possess an adequate supply of air and water, the growth of fertilized forest stands will show no substantial increase unless the application of fertilizers corrected all existing radical deficiencies of nutrient elements. Many of the past fertilizer treatments proved to be totally inefficient because the applied fertilizers did not include the elements necessary for the correction of existing nutrient deficiencies.

All these prerequisites narrow down considerably the general possibilities of the use of fertilizers in silviculture and limit the chances of successful fertilizer treatments to particular cases where such treatments are made with a thorough knowledge of soil conditions.

Considering the limitations imposed by the nature of soils, a satisfactory response of forest stands to fertilizer treatments should be expected on the following soil types:

1. Depleted soils of any textural composition located in humid regions, especially those with a long growing season
2. Sandy soils underlain by root-accessible ground water whose normal summer level lies at least 3 or 4 feet from the surface
3. Substrata of artificially drained and burned-out peat, provided that the ground water table is at a suitable depth
4. Fine-textured soils derived from pure siliceous parent material, such as quartzite and siliceous shales
5. Eroded fine-textured soils which lost their humus-enriched surface layer prior to afforestation
6. Severely burned podzol soils
7. Soils covered with a layer of inert raw humus whose insufficiently rapid decomposition prevents the release of available nutrients

The soils of these catagories occupy an enormous area in the United States. A considerable portion is now supporting struggling forest plantations and "off-site" second-growth stands that are contributing to progressively mounting current expenses. As often as not, this drain of funds proceeds in a manner concealed from the owner of forest property. A skillful application of fertilizers could remove many of these stands from the class of liabilities.

Aside from the composition of soils, the success of fertilizer treatments is influenced by the method of fertilizer application. The description of various methods and their suitability to different stages of forest growth and other conditions follows.

Broadcast application of fertilizers prior to tree planting. Broadcast applications on deforested lands are carried out in the manner that is common in farming practice. The area to be fertilized is determined by an approximate survey and is divided into a number of blocks of convenient size for fertilizer treatment. In the application of soluble fertilizers, the area is plowed, if necessary, and then disked. The desired amount of salt is distributed with a fertilizer spreader or by hand and is worked into the soil by harrowing. In the application of lime, rock phosphate, or other slowly soluble fertilizers the material is plowed under to a depth of approximately 8 inches. The soil is then disked and harrowed.

Broadcast application of soluble fertilizers is largely used in connection with cultivation of legumes or other farm crops for stabilization of soil or improvement of soil fertility. In the absence of a transitional cover crop, treatment of this kind is likely to be more harmful than beneficial. It may promote vigorous growth of weeds and injure roots of seedlings by soluble salts. Because seedlings are planted at a wide spacing, much of the fertilizer applied broadcast is wasted; this is especially true in treatment of sandy soils in which a considerable fraction of soluble salts is rapidly lost by leaching. On some areas, the plowing and disking may initiate acute erosion.

Use of green manure crops. For the establishment of green manure crops, the area proposed for reforestation is treated with approximately 200 pounds of 20 per cent superphosphate and 300 pounds of 50 per cent potassium chloride per acre. On acid soils it may be desirable to use 2 or more tons of dolomitic limestone. The fertilized area is seeded preferably to inoculated legumes, such as red clover and lupines. The legume crop is harvested two years later and the area planted to tree seedlings.

This method provides land well supplied with nutrients and ground well prepared for tree planting. These benefits are usually achieved at little or no expense, considering the return for the sale of hay and seed. On some areas, however, fertilized soils promote the growth of weeds which deprive tree seedlings of water and decrease the increment of the plantation below that on unfertilized soils. Upon closing the canopy and the suppression of weeds, plantations on fertilized soils usually show better growth than those on soils depleted in nutrients, but the loss of increment appreciably decreases the economic benefits of fertilizer treatment. A more serious disadvantage of this method is that cover of green manure encourages egg-laying by June beetles, and the plantation may be severely damaged by larvae, the white grubs. Fortunately, these parasites may be controlled by injections of aldrin synchronized with setting of seedlings (Shenefelt, 1956).

Localized application of fertilizers at the time of tree planting. Application of fertilizers in a planting hole is a simple but laborious method. A hole is dug about 14 inches deep and 18 inches in diameter, and a scoop of fertilizer is placed on the bottom. It is covered with a thin layer of soil and the seedling is planted. This method is largely adapted to the application of *slowly soluble fertilizers* which resist leaching and cannot injure roots by highly concentrated salts. Composts prepared from peat or sawdust, forest litter and raw humus, bone-meal, uramite, rock phosphate, crushed feldspathic or ferromagnesian rocks, and dolomitic limestone are the suitable materials.

Ordinarily, the desired application of fertilizer *in pounds per acre* is divided by 25 to obtain the amount of fertilizer *in grams* sufficient for treatment of one seedling. Suppose the soil needs 1500 lbs. of fertilizer mixture per acre; then 60 g., or approximately 2 ounces, of the material would be applied to each planting hole. This amount of fertilizer is calculated assuming a density of about 2000 trees per acre.

The slowly soluble fertilizers do not encourage the growth of competing weed vegetation, especially herbaceous plants lacking mycorrhizae. However, the cost of hand application of fertilizers limits the use of this method to roadside, shelter-belt, and landscape plantings.

At present, attempts are being made to construct a special attachment for the tree-planting machine which would synchronize the placement of fertilizers with the setting of seedlings. A less elaborate method that may prove to be successful is the use of the double plow machine designed for corn planting.

A localized application of fertilizers including soluble salts or concentrated composts may injure the roots of seedlings and requires lower rates of application and special precautions.

Localized application of fertilizers as a top dressing. Top dressings are usually applied to young plantations which show symptoms of nutrient deficiency.

The amount of fertilizer *in pounds per acre* needed to reestablish soil fertility is divided by 100. This gives the approximate amount of fertilizer *in grams* to be applied per each square foot. The area to be fertilized is determined by the extent of the root systems, which ordinarily is indicated by the spread of the crowns. The fertilizing material is measured by means of a calibrated scoop and is applied around the tree, excluding a zone in the immediate vicinity of the trunk. To prevent the removal of the fertilizer by wind or run-off water, the soil is reworked slightly with a rake or a garden hoe. Readily soluble synthetic fertilizers, such as urea, ammonium sulfate, Ammophos, Nitrophoska, potassium nitrate, potassium sulfate, and Sul-po-mag, are best adapted to this method of application. The success of top dressings may be hindered by the high fixation capacity of the soil, a property which converts fertilizer salts into insoluble compounds and thus renders them unavailable to plants.

In some instances, good results have been obtained with applications of one- or two-inch top dressings of forest litter or leafmold. Working of organic remains into the soil by spading or raking is usually desirable. Spreading slash is one of the forms of top-dressing fertilization (Ramann, 1890; Möller, 1922; Wiedemann, 1931).

Broadcast application of readily soluble fertilizers in forest stands of advanced age. This type of treatment is adapted for plantations and second-growth stands which have already closed their canopy sufficiently to eliminate competition of weed vegetation. The suit-

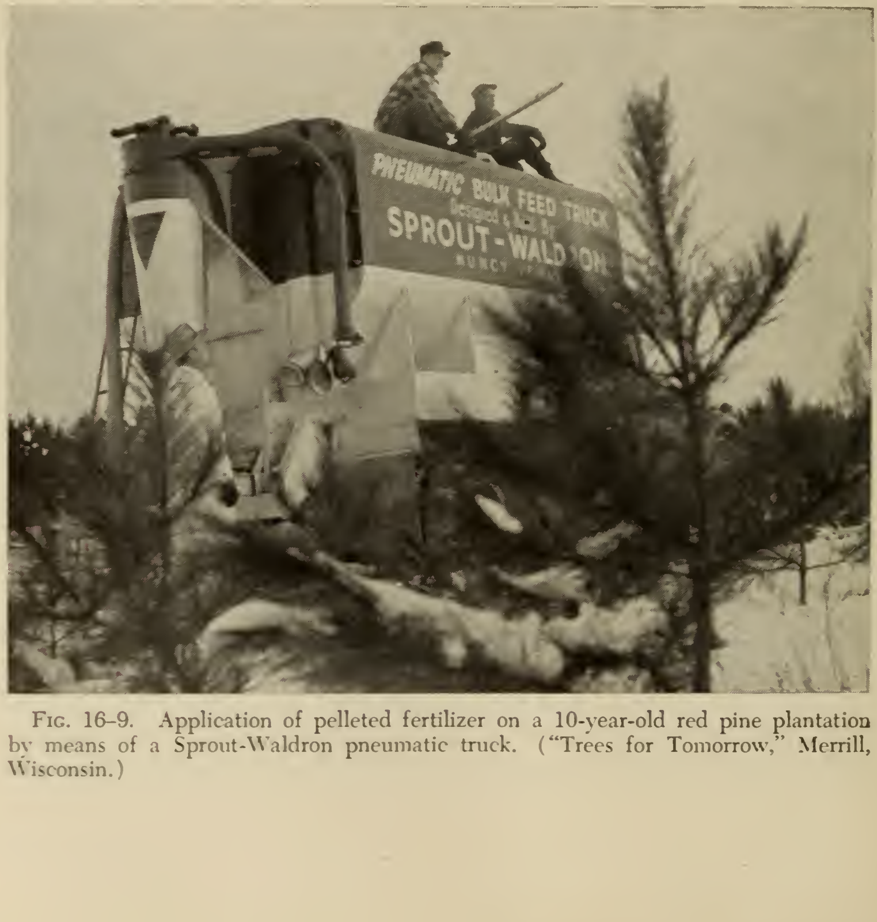


Fig. 16–9. Application of pelleted fertilizer on a 10-year-old red pine plantation by means of a Sprout-Waldron pneumatic truck. ("Trees for Tomorrow," Merrill, Wisconsin.)

able fertilizers include largely soluble salts, such as urea, ammonium phosphate, and potassium sulfate. On some soils these fertilizers must be supplemented by Epsom salt, Sul-po-mag, fertilizer borate, and small amounts of other trace elements. The stands growing on soils of extremely acid reaction or on soils covered with inert raw humus may also need an application of finely ground dolomitic limestone.

In small plantations application of fertilizer can be made by hand fertilizer spreaders. Large-scale treatments may be accomplished by the use of pneumatic blowers of the Sprout-Waldon or Chowning type (Figs. 16–9 and 16–10). Depending on the size of fertilizer particles, the range of these blowers is from 50 to 100 feet. As a rule, the operation of the blower assembly requires creation of corridors in forest stands at a distance of 150 to 250 feet by the removal of one row of trees. Because of the root extension and dispersion of leaf fall, the trees in the center of the treated block are benefited by fertilizer placed at a distance of approximately 25 feet; therefore, the spread of fertilizer does not have to cover the entire area. The removed material usually can be utilized as Christmas trees, fuel, or fence posts. To preserve a proper ratio of nutrients, pneumatically applied fertilizers should be homogenized in the form of pellets

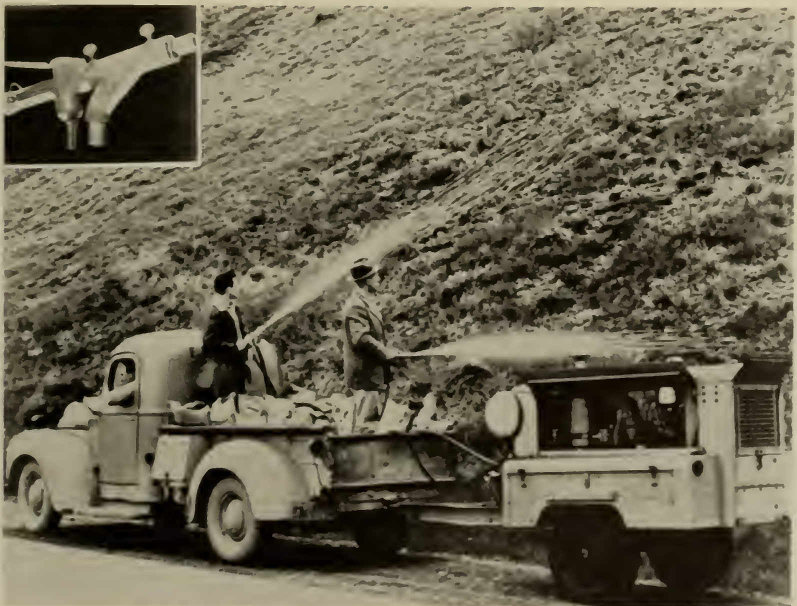


FIG. 16–10. Broadcast application of fertilizer by means of Chowning "Ferti-Blast" unit. The detail of the fertilizer gun is shown in the upper left-hand corner (Chowning Regulator Corp., Corning, N. Y.)

which must have somewhat different diameters and aerodynamic values. In larger plantations fertilizers have been applied from an airplane (Fig. 16–11).

The application of fertilizer in stands of advanced age entraps nutrient ions in a closed cycle of rotating fertility of forest soils. Such ions are utilized by root systems, transported to tree crowns, and later returned to the soils as ingredients of leaf fall. Under such conditions even a small amount of fertilizer, such as 200 pounds of potassium sulfate per acre, may exert its beneficial effect during the entire life of the treated stand.

In using a blower it is difficult to expect a perfect distribution of fertilizer material because of the interference of trees, occasional deviations of pellets by wind, and irregularities in the metering device. The redistribution of applied nutrient salts, however, is promoted by the wide radius of dispersion of forest litter, grafting of tree roots, and mobile soil and forest organisms.

Application of fertilizers in slits or borings. This method is used chiefly in the application of commercial organic fertilizers, less soluble phosphates, and briquette or pellet fertilizers. The slits or borings are made around the base of the tree with a sampling tube, a planting bar, or a narrow spade. A measured amount of fertilizer,

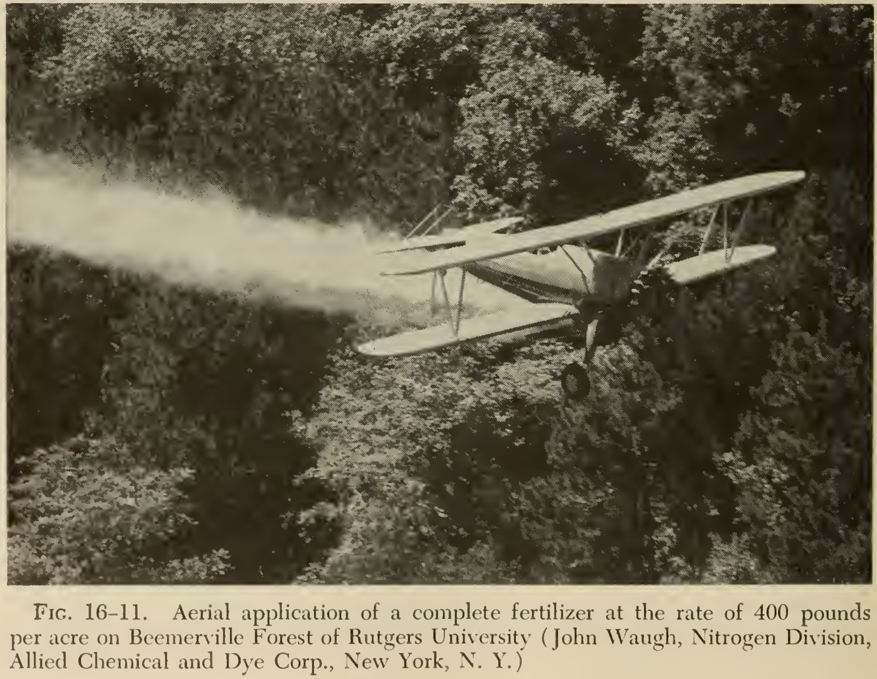


Fig. 16–11. Aerial application of a complete fertilizer at the rate of 400 pounds per acre on Beemerville Forest of Rutgers University (John Waugh, Nitrogen Division, Allied Chemical and Dye Corp., New York, N. Y.)

or a briquette, is placed in the slit, which is then closed with a thrust of the heel. The depth and number of slits vary, depending upon the age of the tree and its root extension. Usually, the depth does not exceed one foot, and one slit is made for each 10 to 20 square feet of the area. It is important to correlate the distribution of the fertilizer as much as possible with the occurrence of the feeding roots. The labor involved in preparation of slits or borings greatly restricts the use of this method.

The application of composted or other organic fertilizers compressed into briquettes appears to be the safest method of tree fertilization (Wilde and Wittenkamp, 1942). This type of treatment is particularly well adapted to soils of high nutrient fixation capacity, but for economic reasons must be confined to growing stock of high monetary or esthetic value.

Application of fertilizers in solution. Treatments with liquid fertilizers have been recently introduced by landscape architects. Such treatments depend on a readily available supply of water.

The fertilizer solution is prepared in a barrel or a tank mounted on an automobile chassis. The solution is stirred by hand or by installed rotating agitators of a propeller type. The liquid is distributed around the trees with either sprinkling cans or a hose. In some cases the solution of fertilizers or growth-promoting substances is forced into the soil under pressure through a hose with a sharp-pointed nozzle. In application the nozzle is thrust into the ground and the liquid is allowed to flow for a certain length of time. In soils with a high capacity for the fixation of phosphates or exchangeable ions, the forcing of solution into the region of root growth may prove to be advantageous. In many soils, however, the pressure method may not have appreciable advantages over the ordinary application of soluble fertilizers as top dressings.

Treatments with anhydrous ammonia. In several trials the application of anhydrous ammonia stimulated a recovery of stands on soils with inert raw humus. The beneficial effect of such treatments was particularly pronounced when the application of fertilizer was combined with reworking of organic remains, the entire operation being performed by an assembly of harrowing discs and ammonia sprayer (Mayer-Krapoll, 1956).

Trials have also been made to encourage the growth of older trees by injections of anhydrous ammonia into the soil surrounding feeding roots. However, the practicability of such treatments may be questioned because of the costly application procedure and the instability of ammonia in soils below the humus layer.

Follow not the system as a blind man followeth a wall.

—Peter the Great of Russia

17

Soils and silvicultural cuttings

Silvicultural cuttings were conducted in the past by technicians who had no facilities for soil investigation. These men of practice were guided by the empirical knowledge inherited from their predecessors or by the "sixth sense" acquired through long contact with managed forests. In the course of years they familiarized themselves with the local behavior of tree species and devised suitable methods of thinnings and regeneration cuttings. Within the boundaries of a certain ecological milieu such methods often proved to be highly efficient. Today there is undeniable evidence that skillful cuttings augment the quality of timber produced and reduce the cost of regeneration. On the other hand, promiscuous use of borrowed methods in unsuitable environments has usually yielded disappointing results.

The urgent task which now confronts specialists in forest soils is to interpret past achievements, as well as failures, in terms of relevant soil conditions. Thus, the former empirical technique may be gradually replaced by more dependable methods. Neither economic requirements nor recent developments in the realm of environmental analysis now justify the "trial and error" procedures in which timber is cut in various ways and the results of the treatments appraised many years later. This approach must be replaced by scientific recording of facts that will provide the necessary information within a short period. Determinations of soil temperature, moisture, available nutrients, activity of soil organisms, and other factors will save the forester much marking of timber, as well as time (Fig. 17–1).

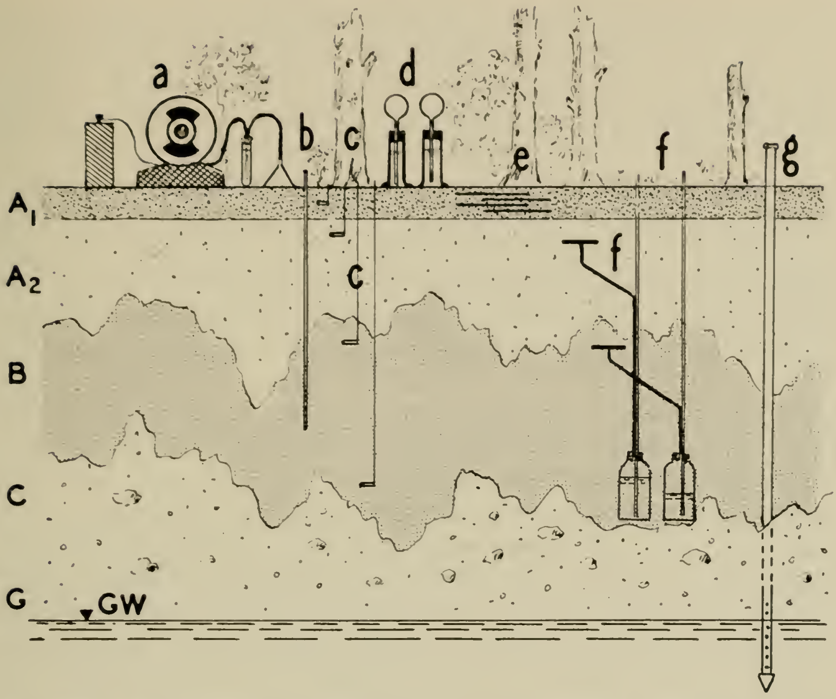


FIG. 17-1. A diagram of an installation for the recording of changes in the composition of soil fertility factors resulting from different silvicultural treatments of stands: (*a*) battery-operated suction pump for the determination of evolved carbon dioxide; (*b*) stoppered small diameter probe for the analysis of gases from deeper soil layers; (*c*) fiberglass blocks provided with thermistors for recording moisture content and temperature of soil; (*d*) calibrated Livingston atmometers for the measuring of evaporation losses; (*e*) Richard's cellulose and protein cords for determination of activity of microorganisms engaged in decomposition of organic matter; (*f*) alundum tension lysimeters for recording the losses of percolating water and nutrient salts; (*g*) water well for observation of the position of the ground water table, electrometric analyses of ground water, and introduction of isotopic tracers for detecting the extent of the capillary fringe.

This chapter deals with silvicultural cuttings and the correlative dynamic changes which take place in the composition of soil under the influence of skidding, altered leaf fall, reduced removal of transpirational water from the deep soil layers, and modifications in the stand's microclimate.

GENERAL PRINCIPLES OF SILVICULTURAL CUTTINGS

Diseased and injured trees which may serve as breeding centers for parasites are removed in all silvicultural cuttings. Struggling, suppressed trees, spreading "wolf" trees, and trees of sprout origin are cut if they interfere with the growth of valuable trees. In all cuttings the exposed boundaries of stands are protected by shelterbelts of border trees which are released to develop deep crowns. In silvicultural operations covering large areas the formation of frost pockets is precluded by cutting passages for air circulation.

In many instances, recommendations are made for the elimination of trees of so-called "undesirable species." However, the classification of tree species into "desirable" and "undesirable" is usually based on the immediate prospects of utilization and is of questionable significance. The commercially inferior species may often prove to be of great silvicultural value; they may ameliorate the microclimate, improve the soil, control the growth of weeds, protect natural reproduction from frost and sunscald, act as trainers of crop trees, reduce fire hazard, check the spread of parasitic organisms, and provide sustenance for wild life.

Of great importance is the fact that the removal of even a few trees appreciably alters the intensity of light and the temperature, moisture, and air movement within the forest stand (Franklin, 1955). All these modifications, in turn, produce profound changes in the composition of the soil (Krauss, 1911). Therefore, by means of skillful cuttings the forester can often modify the environmental conditions to suit the requirements of different tree species (Morozov, 1912; Dengler, 1930). Contrary to this, indiscriminate cuttings, especially cuttings conducted without regard to soil conditions, may produce highly unfavorable results. Among such results the following are of prime importance:

1. Establishment of natural reproduction of tree species which for ecologic or economic reasons eventually become a liability.
2. Encouragement of the growth of weeds and other undesirable members of forest stand competing for light, moisture, and nutrients with crop trees and valuable natural reproduction.
3. Promotion of invasion by parasitic organisms through modification of the environment, the encouragement of parasite vectors, or the suppression of natural agents of parasite control.
4. Adverse alterations in the biological makeup of the surface soil layers, leading either to depletion of soil organic matter or the development of inert raw humus and retarded release of available nutrients.
5. Encouragement of soil erosion and formation of avalanches.
6. Increase in the compaction of soil and subsequent losses of precipitation water through evaporation and runoff.
7. Increase of fire hazard.
8. Decrease of the resistance of the forest stand against wind and other adverse climatic factors.

9. Unfavorable changes in the position of the ground water table or saturation of the soil with superficial vadose water.

Other aspects of forest growth to be considered in silvicultural cuttings include competitive and symbiotic relationships of species and specimens constituting forest stands.

All members of forest stands are constantly striving to seize living space either for their individual development or for the growth of their offspring. Unless checked by man, the forest invariably becomes "an over-production of trees on a certain area." The resulting congestion exerts profound changes upon the growth, quality, reproduction, stability, and genetic rating of forest stands (Paczossky, 1921).

Isolated trees live their normal life span, whereas most of the trees in a dense forest are gradually killed by their neighbors. In a young forest there may be as many as 50,000 seedlings per acre, but in a forest stand one hundred years old there may be only 100 trees per acre. Through this enormous mortality nature eliminates weak individuals incapable of competing with their more vigorous associates (Darwin, 1859). In too heavily thinned stands there is no struggle for life; hence unfit specimens have a chance to grow and reproduce. Thus, the elimination of competition tends to bring about a general degradation of the present stand, as well as degeneration of the future forest which may originate from inferior seed trees (Mathieu, 1878).

Competition attains particular severity among the members of different species or different groups of forest vegetation. Many attempts to establish mixed stands by alternation of antagonistic trees, such as jack, red, and Scotch pine, have led to premature deterioration of less vigorous species. These experiences were responsible for the development of mixed stands made up of small groups of various species. Mixed stands of tolerant hardwoods and conifers, the silvicultural ideal, cannot always be maintained without rigid artificial control because of the incompatibility of different tree species—light-grabbing leanings of some, podzol-forming tendencies of others.

The social structure of forest stands entails not only the struggle of trees for life but also their cooperation in growth (Morozov, 1912); the latter may range from a mere commensalism to symbiosis and to outright sacrifice (Braun-Blanquet, 1951; Leibundgut, 1951). The planting of white birch and other "trainers" to encourage the growth of spruce seedlings is a commonly quoted illustration of "cooperation" between tree species. Pioneer stands of aspen which protect natural reproduction of spruce and fir and become, in time, the victims of their charges present an example of martyrdom in the forest community. Conifers with a somewhat greater aptitude for commensalism, like white pine, often permit maple, beech, basswood, hornbeam, and oak to exist, but as conquered slaves in the dark understory; the deep root systems and base-enriched foliage of the hardwoods then provide the rulers with fertilizing material. Basswood, white ash, and many other deciduous species that never occur in pure stands appear to be virtually dependent upon the hard maple or oaks forming the bulk of the forest. The yellow birch persistently accompanies hemlock across gravelly ridges, hardpan podzols, lacustrine clays, and semiswamp ground; this case of noncommittance is difficult to explain on the basis of available knowledge.

These sociological relationships of trees vary with the nature of the habitat; the same species which peacefully coexist on one soil may on other soils segregate to become victors and victims. Therefore, the success of silvicultural cuttings depends upon the correct appraisal of the inherent social traits and mutual effects of different tree species on a given site.

TYPES OF CUTTINGS

Clear cutting exposes the area to climatic extremes as well as invasion of weed vegetation and often leads to serious deterioration of the site. From a biological viewpoint, Rubner (1927) regards clear cutting as a drastic intrusion into the life of the forest, an operation which upsets the equilibrium of the entire population of the forest community. If cut-over land is not reforested for many years, the soil may suffer appreciable loss in its content of organic matter and in its productive capacity (Billings, 1938). Table 17–1 compares the state of fertility factors in soils of virgin stands and adjacent old cut-over areas (Wilde, 1946). Similar observations have been made by European investigators (Burger, 1922; Wittich, 1930).

In spite of all its shortcomings, clear-cut logging cannot be entirely excluded from rational forest management. Frequently it is dictated by economic or ecological conditions, the occurrence of parasitic organisms, or inferior growing stock that must be replaced by more suitable species.

The principal advantage claimed for clear cuttings—their simplicity—holds true only when forest exploitation is guided by the formula, "cut out and get out." Clear cuttings which are not synonymous with the plundering of forest resources require a thorough knowledge of the local effect of wind, danger of frost, vulner-

TABLE 17-1

Analyses of the Surface Soil (7-inch layer) from Virgin Forest Stands and Adjacent Cut-over Areas in Northern Wisconsin

Location	Reaction (pH)	Base exchange capacity (m.e./100 g.)	Total N (%)	Available P_2O_5	Available K_2O	Replaceable Ca	Replaceable Mg
				(lbs. per acre)		(m.e./100 g.)	
Stand of red pine and white pine, 150–170 years old; Vilas Co.	5.7	6.3	0.117	58	160	2.9	0.9
Adjacent cut-over area	5.9	3.9	0.030	23	70	1.8	0.4
Stand of hard maple, basswood, and associates, 200 years old; Forest Co.	6.3	14.7	0.205	145	270	9.4	2.4
Adjacent cut-over area	5.7	8.9	0.064	70	100	3.3	1.8

ability of soil to erosion, and other conditions which determine the correct direction of cuts and the appropriate size and shape of the logged areas.

Partial cuttings are classified as weedings, thinnings or improvement cuttings, and regeneration cuttings; this classification is based on the age of the growing stock and the purpose of treatment.

Weeding or **cleaning** are the terms applied to the elimination of trees and shrubs in dense young plantations and natural reproduction. In European practice, weeding may be divided into as many as three cuttings. The first, conducted when reproduction is from three to seven years old, has a "negative tendency": it seeks to eliminate only the inferior material. The second weeding is characterized by a "positive approach," for it aims to release the genetically superior trees. The third, pre-thinning cutting, crystallizes the composition of the growing stock for its next critical stage of development—the struggle for survival in a closed canopy. This cut is of particular importance in natural reproduction including both tolerant and light-demanding species, for example, fir, spruce, pine, and larch. Mixtures of this kind, attained through careful weedings, are justly the pride of German foresters.

Weeding operations do not exert an important influence on the composition of the soil. Nevertheless, the forester conducting such operations must have a thorough knowledge of the soil productive potential in order to regulate weeding to favor the best-suited tree species.

Thinning is a partial cutting of a stand of sapling size or larger. Depending on the nature of growing stock and merchantability of material, it is conducted in one or several operations. The chief purpose of thinning is to increase the quality of the stand by eliminating superfluous and inferior trees. To a large extent, the thinning of forest plantations should be regarded as surgery which aims to improve the genetic composition of the growing stock. In the past foresters regarded thinning as a measure increasing the volume of timber produced per unit area, an assumption which often proved totally fallacious. According to the results of recent investigations obtained by some foresters (Tkachenko, 1952), the total production of wood often remains about the same in thinned and unthinned stands. The thinnings contribute, however, to the better form and larger diameter of trees, thus increasing the value of the final crop (Schädelin, 1942). Thinnings conducted on the basis of abstract formulas and without regard to environmental conditions may not only decrease the rate of stand growth but may lead to complete destruction of the stand.

Thinnings of older stands, especially those comprised in a large part by inferior species, sprouts, and diseased or injured trees, are referred to as **improvement cuttings** or **sanitation cuttings.** If, in the process of partial cuttings, the stand is underplanted by species foreign to the present growing stock, the operation is called **conversion cutting.**

Regeneration cuttings consist of the gradual removal of mature timber to obtain natural reproduction of desired tree species. Such cuttings are usually extended over a period of twenty or more years. Depending on conditions and the personal preferences of the forest manager, regeneration cuttings are conducted on the entire logged area, a succession of narrow parallel strips, concentric strips emanating from small regeneration centers, or progressively enlarged wedges (Vanselow, 1931; Kostler, 1950; Hawley and Smith, 1954).

In regeneration of mixed stands, the desirable composition of natural reproduction can seldom be obtained without subsequent careful weeding.

INTENSITY OF CUTTINGS

Regardless of the system used, the success of partial cuttings depends upon the intensity of individual cuts or the quantity of timber removed in a single operation.

The spacing of tree trunks after cutting or thinning may vary from 6 feet to as much as 100 feet. The appropriate distance between single trees is largely determined by the extent of their crowns, because the density of the canopy controls the growth of competing vegetation, decomposition of organic remains, content of soil moisture, and other important conditions. Therefore, the intensity of silvicultural cuttings may be classified into three types: **light cuttings,** which preserve an unbroken crown canopy; **moderate cuttings,** which slightly break the canopy so that the crowns of the remaining trees have space for increased development; and **heavy cuttings,** which leave a distance between the crowns of the remaining trees at least as great as the average crown diameter in the stand.

Light cuttings or thinnings are required under the following conditions:

1. On rock outcrops, skeletal soils, and other shallow soils where there is danger of windfall.
2. On steep slopes, to prevent rapid runoff and erosion.
3. On hot and dry slopes or sites exposed to dry winds, to conserve moisture and retard decomposition of organic remains.
4. On highly fertile soils, to control the rank growth of competing vegetation.
5. On clay soils with unstable structure where heavier rainfall may lead to the sealing of the soil surface and subsequent puddling of the soil.
6. On soils predisposed to a rise of the ground water table.

Moderate cuttings or thinnings are the most common. On one hand, this kind of cutting should materially improve the composition of the stand, eliminate superfluous competing trees, and secure enough light for crop trees; on the other hand, it should not promote the growth of competing vegetation or decrease soil fertility.

Heavy cuttings or thinnings are permissible only in rare instances, for example:

1. On cool and moist exposures, particularly on northern slopes, to provide more light for natural reproduction.
2. On podzol soils to encourage more rapid decomposition of peat-like raw humus.
3. When it is necessary to eliminate inferior or diseased trees.
4. On organic soils of low productive capacity.

SILVICULTURAL CUTTINGS ON DIFFERENT SOILS

This section reviews various approaches to silvicultural cuttings which may be suitable on the more important habitats of the temperate region.

MELANIZED SANDY SOILS OF FLUVIAL ORIGIN

The predominant forest cover on nonpodzolic sandy soils of glacial outwash, lacustrine deposits, and river terraces consists largely of light-demanding pines with occasional intrusions of scrubby oaks, aspen, birch, and other pioneer trees. The productive capacity of these soils is limited by their low water-holding capacity and subsequent shortage of moisture. The soils derived from siliceous rocks or those subjected to previous agricultural use may also be deficient in some essential nutrients.

Because of their texture, freedom from stones, and absence of illuvial horizons, melanized sandy soils are well adapted for the determination of their physical and chemical properties and thus provide excellent opportunity for studies of the dynamic changes resulting from partial cuttings. Much valuable information on behavior of these soils can be obtained by simple determinations of soil temperature and moisture, using thermometers and balance, or moisture blocks and thermistors. The analytical techniques are described by Wilde and Voigt (1955).

Thinnings. Alterations in the composition of soil attain decisive importance in silvicultural cuttings only after a forest stand closes its canopy and trees enter into acute competition for the three vital sources of their existence—light, water, and nutrients. In stands of nonexacting pines, such as jack pine, red pine, and Scotch pine, this critical stage of growth is reached when trees are approximately twenty years old, the age which usually coincides with the initiation of thinnings.

One of the aims of the thinning operation on these soils is to reduce competition of trees for moisture and to spend the available supply of water for the production of a few trees of large diameter instead of many trees of small diameter. To achieve this purpose, the soil should be meticulously protected from direct sunlight by the stand's canopy. This alone can preclude the rapid decomposition of organic remains, the loss of moisture through evaporation, and especially the pumplike action of transpiring grasses which invade the exposed areas. Therefore, the thinning should be confined largely to the suppressed trees so that the canopy is reduced in the vertical rather than the horizontal direction. Such treatment of the stand, characteristic of the German school established by Hartig and Cotta (Dengler, 1930), allows more precipitation to reach the ground but protects the soil from the direct rays of the sun by the crowns of dominant and codominant trees.

On soil deficient either in moisture or nutrients there is no expression of dominance and natural stands of hard pines consist entirely of small-diameter trees. If such stands are not reduced in density by timely thinnings, they are likely to be damaged by wind (Fig. 17–2).

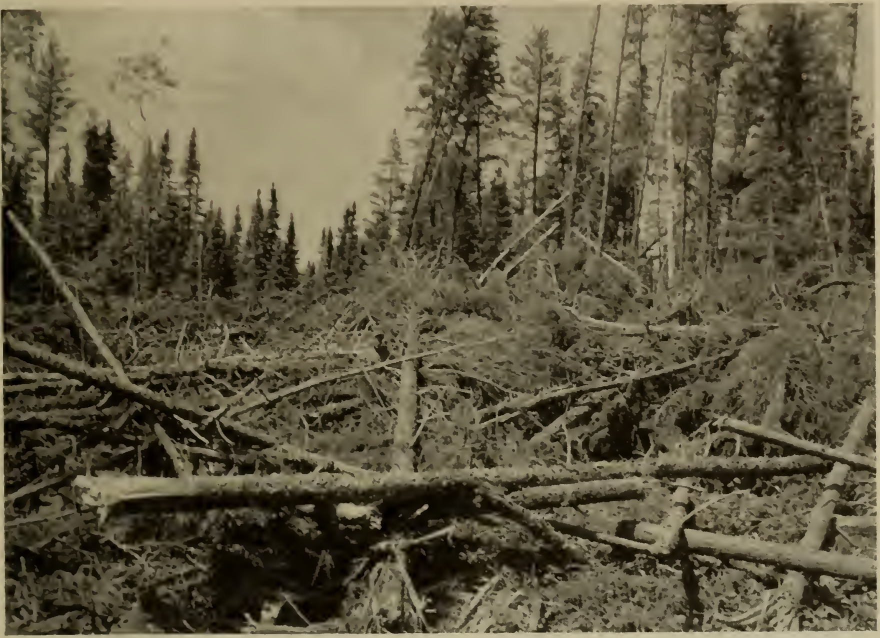


FIG. 17–2. Wind damage of a jack pine stand with a poorly balanced height-diameter ratio, a frequent finale in the growth of unthinned stands on soils of low productive capacity. (Nekoosa-Edwards Paper Co.)

Occasionally pine stands include a considerable percentage of deciduous species of poor quality, particularly hybrid oaks. As a rule, the natural tendency of the forest manager is to free the stand of the nonmerchantable material. However, the wholesale elimination of broad-leaved trees may deteriorate soil conditions and increase the hazard of fire. Moreover, a decrease in the supply of game food may eliminate some of the natural agents of parasite control and thus render pure coniferous stands vulnerable to destruction.

Conversion cuttings. On many areas of melanized sandy soils, fire and logging changed pine forest into volunteer stands of oaks and other deciduous trees. The supply of either water or nutrients is not sufficient in these soils to produce high yields of deciduous species. Hence, such stands should be converted into pine forest by underplanting suitable species of pines after the density of the stand is appropriately reduced. The release of underplanted pines should be accomplished as fast as possible with consideration of the danger of frost, sunscald, and parasitic insects, especially the weevil. Occasionally, the rate of release cuttings must be slowed to prevent the invasion of grass and a growth of sprouts.

Regeneration cuttings. The regeneration of light-demanding pines presents a problem whose solution requires a thorough consideration of silvicultural and economic aspects. The natural reproduction of hard pines on sandy soils at times becomes a curse rather than a blessing. The cost of weeding, the irregular spacing, the mixed genetic origin of the growing stock may force the forest manager to the drastic measure of plowing under young natural stands and replanting the areas with a stock of selected elite trees.

If conditions do not favor artificial reforestation, careful attention should be paid to the direction of regeneration cuttings. On sandy soils of the podzol regions light-demanding pines usually reproduce best on warm southern exposures, where light is abundant. Consequently, regeneration cuttings must proceed in a northerly direction. This approach is particularly suitable on sandy soils with a high ground water level. On sands of warmer regions, however, the southern exposure may be too hot and dry even for the drought-resistant

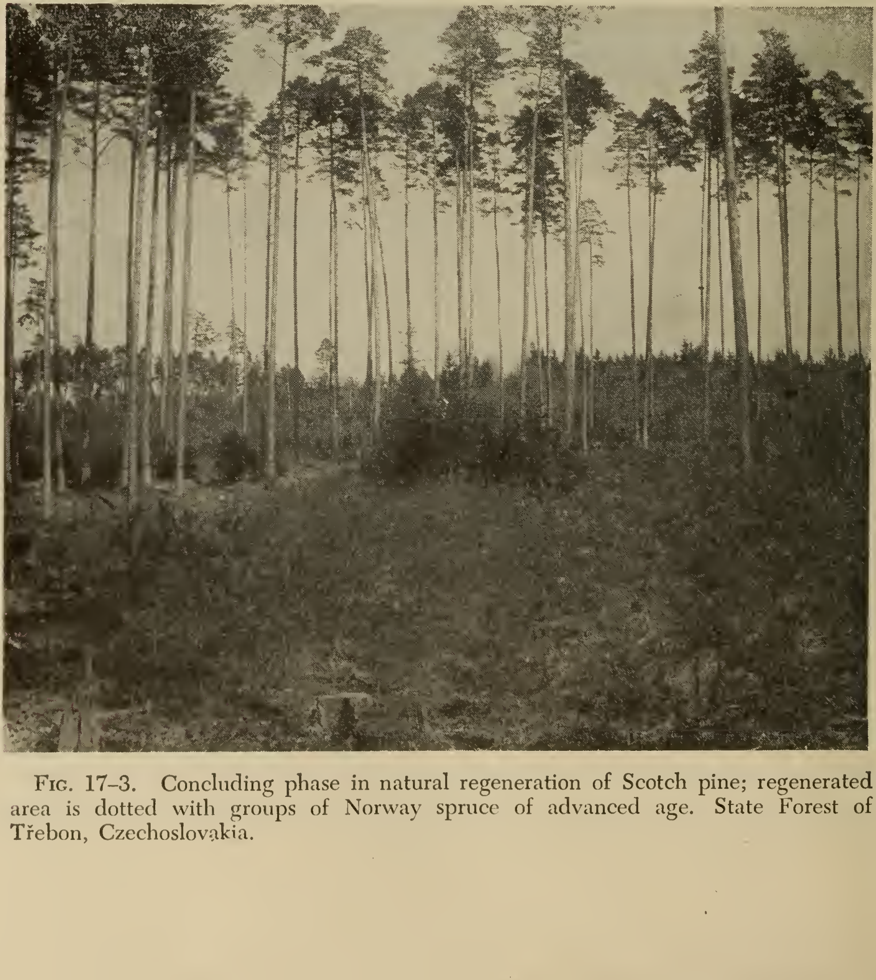


Fig. 17–3. Concluding phase in natural regeneration of Scotch pine; regenerated area is dotted with groups of Norway spruce of advanced age. State Forest of Třebon, Czechoslovakia.

pines. Consequently, logging must proceed from north to south. Observation of the natural reproduction, as well as recordings of local environmental conditions, will indicate the correct direction of cuttings (Fig. 17–3).

PODZOLIZED SANDY AND SANDY LOAM SOILS

By virtue of their pedogenic origin, these soils support mostly conifers, with an occasional admixture of birch and aspen or other deciduous trees. The silviculturally important features of light-textured podzolized soils include their ectorganic layers and compacted or indurated accumulative horizons.

Weedings. Weedings of young coniferous stands on these soils should not eliminate all of the volunteer deciduous species. The incorporation of the litter of broad-leaved trees improves both the physical and biological properties of organic layers and thus precludes or retards the accumulation of inactivated organic debris.

Thinnings. Thinnings of coniferous stands may be conducted with considerable intensity to promote decomposition of litter and the continuous release of nutrients. Opening of the canopy on these soils is usually permissible because of the scarcity of competing vegetation (Fig. 17–4). On soils with indurated horizons, however, the removal of trees should not permit the periodic accumulation of unabsorbed vadose water and saturation of the leached horizon. Careful determination of moisture content in the A_2 layer during the critical periods should indicate the appropriate intensity of cutting.

Although podzol soils possess certain unfavorable characteristics, they occupy a unique position in regard to thinning operations. They belong among the few types of soils on which thinning may improve not only the quality but also the rate of growth of the treated stands. This takes place because of the fertilizing effect of nutrients released from organic remains under the influence of altered conditions. At times, however, such a "self-fertilization" of the soil must be stimulated by broadcast applications of lime.

The influence of the removal of trees on the behavior of the raw humus layer can be detected by systematic observations of cellulose and protein decomposition (Richard, 1945), the determination *in situ* of carbon dioxide evolution, and recording of the release of available nutrients by means of tension lysimeters (Cole, 1957).

Release cuttings. The improvement of older reproduction of pines mixed with aspen or birch is carried on by cuttings which aim to release the valuable conifers from suppressing deciduous pioneers

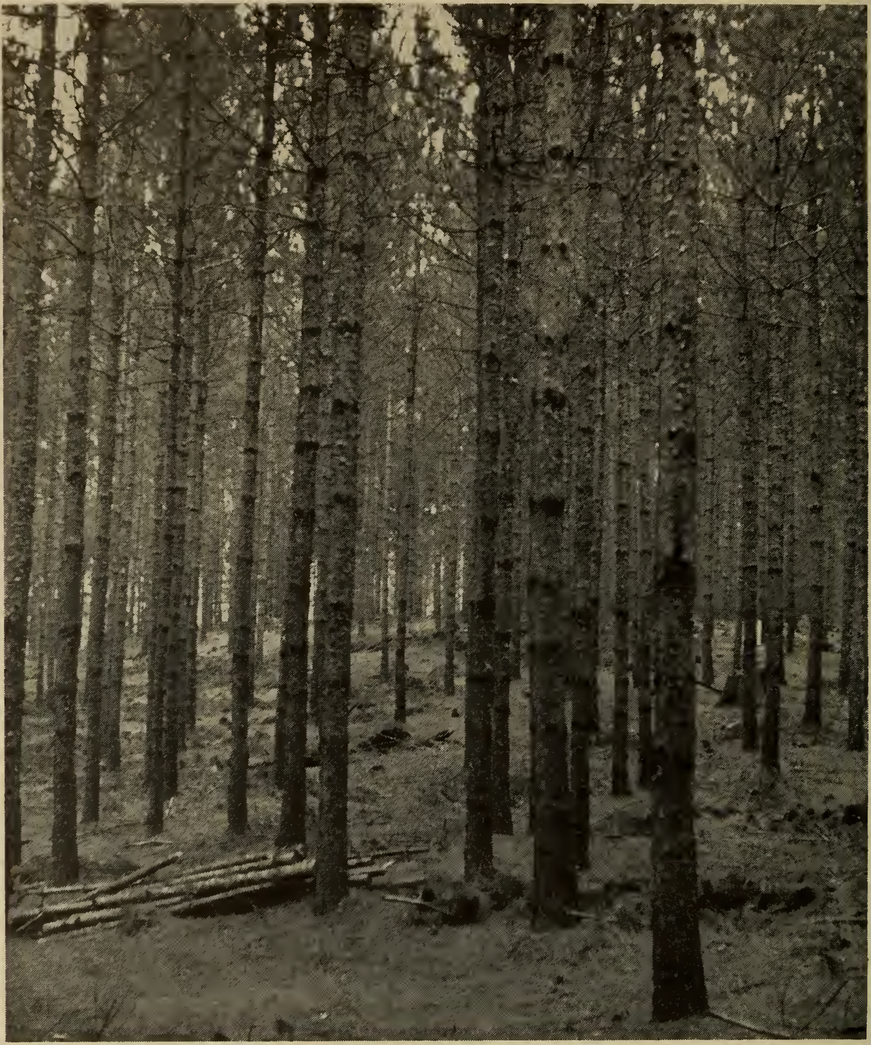


Fig. 17–4. Twice-thinned, 35-year-old plantation of red pine on a podzolized sandy soil. Note the absence of competing vegetation. Star Lake plantation in northern Wisconsin. (F. G. Wilson and Wisconsin Conservation Department.)

(Fig. 17–5). These liberation cuts, peculiar to American silviculture, approach in their essentials the French *l'éclaircie par le haut,* a thinning that interrupts the canopy of the dominant stand but maintains an undisturbed understory for protection of the soil. Theoretically, in a stand thinned by this method, the selected crop trees should have their "crowns in sunlight, stems in shade, and roots in damp

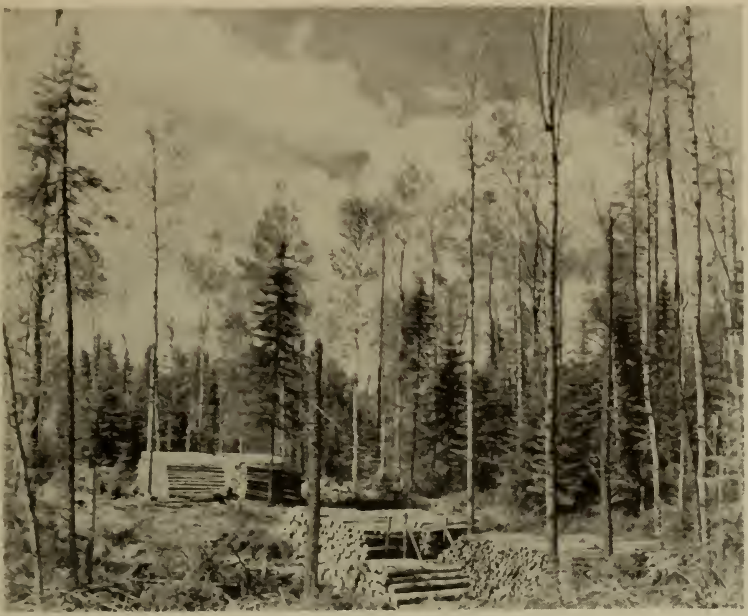


FIG. 17–5. Partial cutting of aspen and paper birch pulpwood aiming at release of the understory of conifers. (Nekoosa-Edwards Paper Co.)

ground." The latter condition, however, is not easily attainable in drier regions and on coarse sandy soils.

Regeneration cuttings. Regeneration cuttings of spruce, fir, hemlock, and other conifers on podzols are complicated by several antithetical conditions. A thick layer of matted raw humus retards the reproduction of trees, even conifers that have saprophytic tendencies. To promote the activity of soil organisms and the decomposition of organic remains, the intensity of light and the temperature should be increased by a rather heavy cutting. On the other hand, the reproduction of tolerant conifers is likely to suffer from frost and sunscald upon a sudden exposure. Moreover, trees on podzol soils develop superficial root systems and hence are vulnerable to windfall, especially if the stand has been weakened by a heavy cutting. The methods which reconcile these contradictory requirements are group-selection cuttings (Gayer, 1876) and wedge cuttings (Eberhard, 1922).

In the group-regeneration method, the trees are removed in small patches, preferably where some reproduction is already present. The trees are felled in a fanlike formation away from the reproduction. The skidding of trees tends to break up the raw humus layer and encourages the establishment of natural reproduction. In five or more years the cutting area is enlarged by a second concentric cut, or a cut extended in a direction which offers the best protection to natural reproduction. Similar cuts are made at intervals of several years, depending upon the condition of young growth, until the forest in the entire block is regenerated (Fig. 17–6).

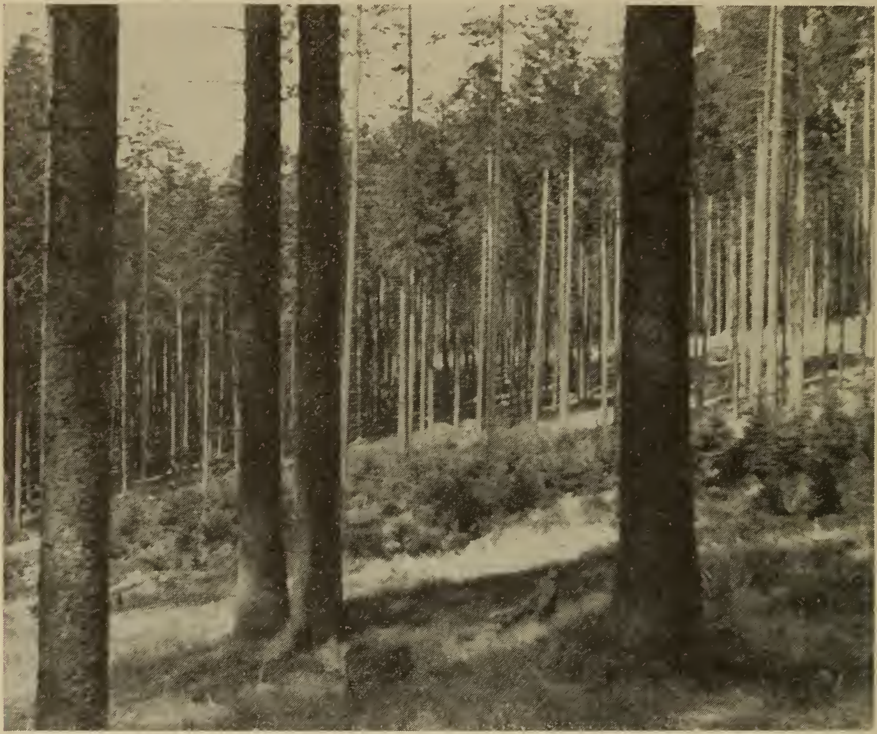


Fig. 17–6. Natural regeneration of Norway spruce by a group selection method of cuttings. Goldenhöhe Forest, Central Bohemia.

Wedge cutting is now considered in Germany as one of the most efficient methods of both utilization and regeneration of forest stands. The initial cuts are made at suitable distances in the form of narrow wedges on the side of the block away from the prevailing wind. The regeneration of the stand is achieved by progressive shelter-wood strip cuts extending outward on both sides from the center of the strip (Fig. 17–7).

This type of cutting aims to minimize the danger of windfall, to obtain a long regeneration front, and to protect reproduction from skidding and climatic extremes. On dry slopes the position of wedges is chosen to minimize the exposure of reproduction to direct

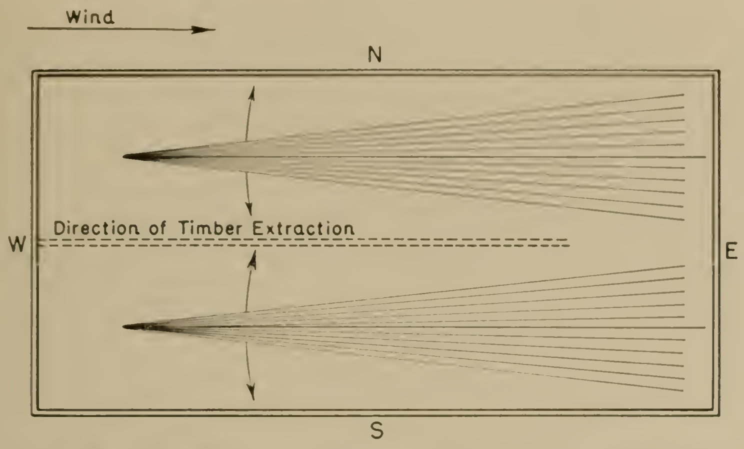


FIG. 17–7. Natural forest regeneration by wedge cuttings. (After Eberhard, 1922.)

sunlight. The regeneration of the stand may be encouraged by increasing the intensity of cuttings and by scarification of the raw humus layer. On sites where natural reproduction is exposed to the drainage of cold air, the point of the wedge is opened to make a lane through which descending winds may pass.

In many respects wedge cuttings approximate the approach of the shelter-wood strip system originated by Wagner (1907, 1915). Although the Wagner method was found inapplicable under many conditions, it represents an example of a silvicultural treatment which takes into account a great number of environmental factors. The regeneration is accomplished in three operations: a regeneration cut, a release cut, and a final cut. These cuts are conducted on a succession of strips about 50 feet wide. In this method the primary emphasis is placed on the choice of the exposure for the regeneration front. In many locations of the temperate zone, regeneration is best achieved by cutting the stand from the northwest to the southeast. This orientation of cuttings protects natural reproduction from dry eastern winds and midday sun and permits free admission of western rains, formation of abundant dew, and accumulation of snow; the latter moderates the browsing of deer and retards early growth of seedlings, thus protecting them from damages by late frosts. Depending on altitude, topography, and direction of the prevailing wind, the direction of cuts is reoriented to comply with requirements of the local environment. In localities where the regeneration front is exposed to strong winds, side protection is achieved by the arrangement of cuttings in a steplike fashion (Fig. 17–8).

In spite of the several deficiencies of its original rigid pattern of cuttings, Wagner's method presents a unique example of the scien-

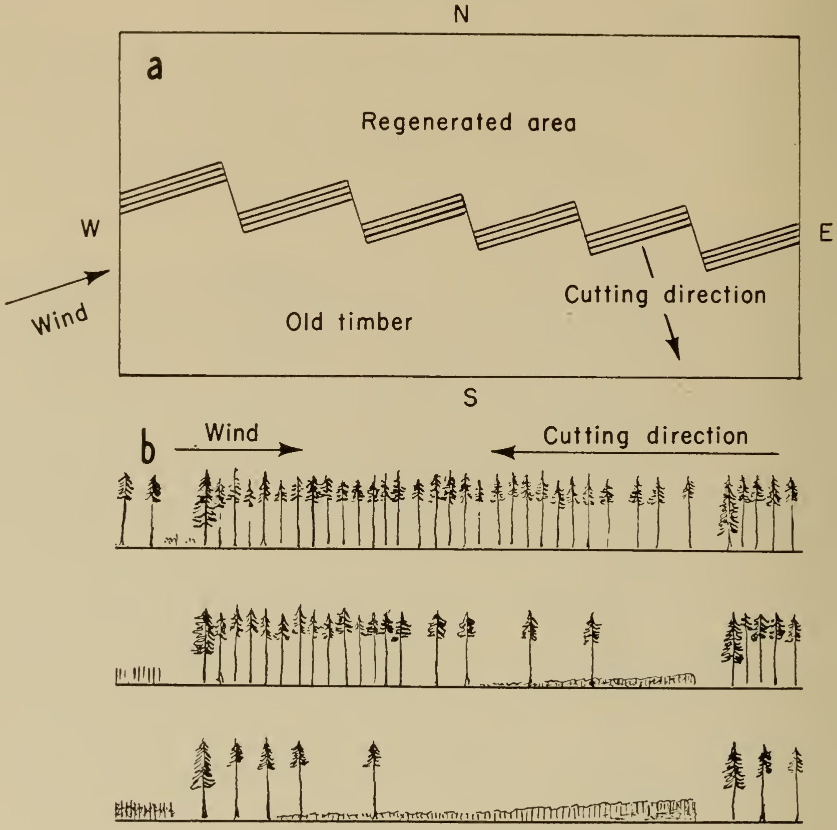


FIG. 17-8. Ground plan (*a*) and side view (*b*) of regeneration cuttings by shelterwood strip method in steps from NNW to SSE conducted on a tract approximately 40 acres in size. (Adapted from Ch. Wagner, 1915.)

tific correlation of forest practice with environmental conditions. There is little doubt that in the future Wagner's ideas, reinforced by instrumental recording of soil and microclimatic factors, will play a prominent part in the utilization of both North American and Eurasian forests.

MELANIZED OR MULL LOAMS

The predominant forest cover of these soils is composed of exacting hardwoods, such as hard maple, basswood, white ash, white oak, and tulip poplar. A thin layer of litter, a deep horizon with incorporated humus, and the absence or near absence of leaching of the soil are the important characteristics to be considered in partial cuttings.

Improvement cuttings. These soils are predisposed to the invasion of weed species that often have a high sprouting capacity. For these reasons the stands are rarely touched by a machete or an axe until the trees have entered a state of acute competition. Even then, heavy cuttings may encourage the growth of the less desirable species or serve to convert trees of seed origin into short-lived sprouts. The release of the best crop trees, therefore, must be accomplished very slowly, eliminating the inferior material by an axe or a girdling knife. The use of toxic arboricide compounds has not been in practice long enough to justify their recommendation. The benefits gained by the use of toxic chemicals may be offset by their harmful effect on soil organisms and soil fertility.

Any improvement cuttings in stands of exacting species should be preceded by a complete analysis of soil fertility. It is not uncommon that costly treatments of second-growth hardwoods are performed on soils of insufficient productive capacity, which dooms the treated stand to premature deterioration (Wilde, 1954; Keller, 1957).

Conversion cuttings. Because of financial considerations, attempts are often made to replace hardwoods with conifers, a conversion which may be fully justified on podzolized soils. On soils not influenced by podzolization process, however, the introduction of conifers may be foreordained to failure. The underplanted coniferous seedlings will have to face on melanized soils the onslaught of the entire hardwood community, including sprouts, seed volunteers, herbaceous vegetation, disease-transmitting host-plants, hostile microbes, and last, but not least, members of hardwood fauna living below and above the ground line. Melin (1946) has shown that even dead leaves of maple and other hardwoods carry growth-inhibiting substances which may be toxic to symbiotic fungi of conifers.

Regeneration cuttings. The thin layer of litter and the humus-enriched mull horizon make an ideal seedbed, so the establishment of natural reproduction seldom presents difficulties. However, a heavy cutting on these soils may lead to the invasion of weeds and sprouts which suppress the seed reproduction. Also, a heavy cutting may hasten unnecessarily the decomposition of litter and cause a loss of nutrients, especially nitrogen. For these reasons, hardwood stands on mull loams ought to be cut very conservatively, usually according to the principles introduced by Heyer (1854). Regeneration by this method involves four successive cuts: preparatory cut, seed cut, release cut, and final cut. The entire operation may extend over a period of twenty to forty years. The control of the composi-

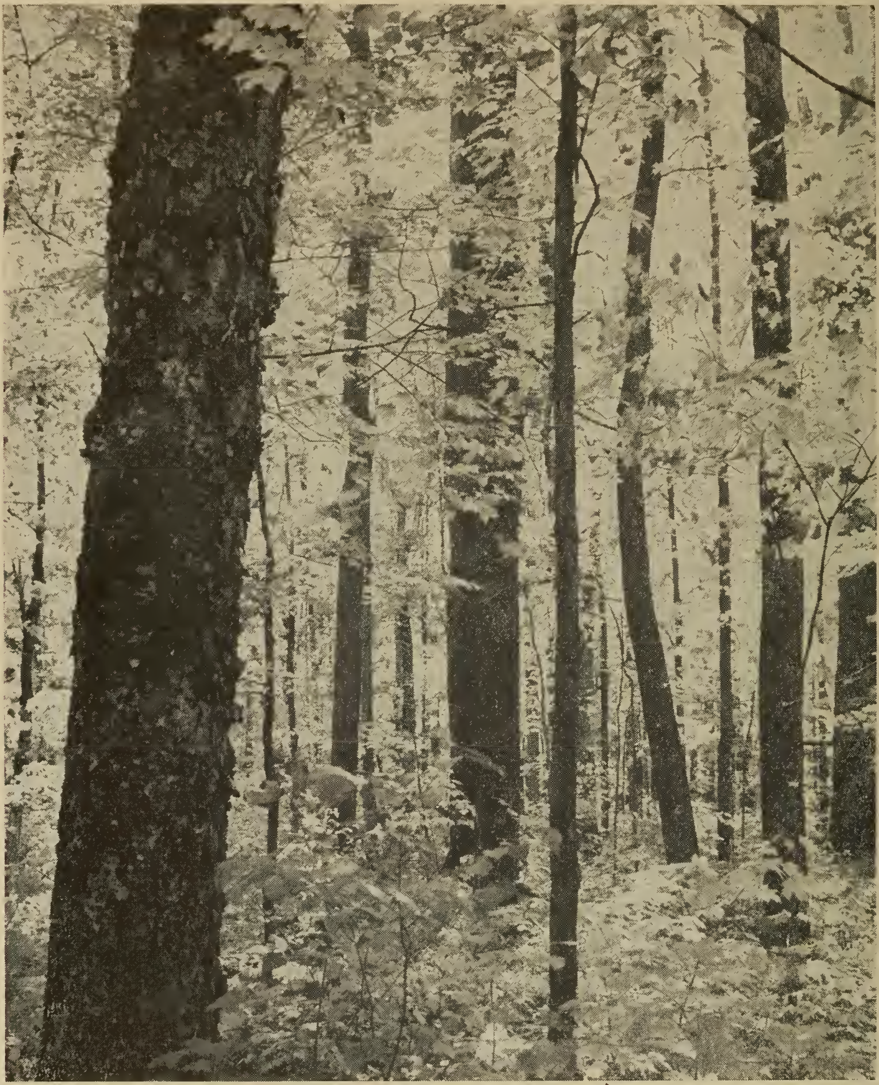


Fig. 17–9. A mixed stand of sugar maple and other northern hardwoods on melanized morainic loam—an example of the selection cutting system of forest exploitation. (Wisconsin Conservation Department.)

tion of the future stand is achieved partly by eliminaton of unthrifty old trees and partly by maintenance of a dense canopy over the reproduction of undesirable species. At times regeneration cuts are accompanied by weeding or underplanting.

The geologic origin of soil and the content of soil nutrients often play decisive roles in the determination of the ultimate composition of a stand. For instance, in oak-beech-maple stands on fertile traprock soils of central Europe, oak grows more rapidly than beech and maple, which remain as a suppressed understory. Therefore, if it is desirable to maintain a mixture of all three species, a special effort is made in cutting to protect beech and maple. On the other hand, in cutting stands of the same composition on soils derived from calcareous shales, it is necessary to retard the reproduction of beech as much as possible, for it may suppress the other species, particularly oak.

Hardwood stands on melanized loams can also be utilized and regenerated by frequent selection cuttings spread over the entire stand area. The intensity of cuttings and the removal of individual trees are largely based on the current diameter increment, and the method requires frequent cruising of the growing stock. In time, selection cuttings convert even-aged stands into a "lasting forest" (Dauerwald) composed of all age classes (Fig. 17–9).

This type of forest management, known under the terms "experimental method" and "method of control" (Biolley, 1920), is ideal from the standpoint of esthetics, soil conservation, game preservation, and forest protection. However, it does not always meet the requirements of economics, because of the high cost of frequent logging operations. Moreover, the canopy of many-storied stands presents a serious obstacle for penetration of rain; this may be responsible for greatly depressed increment of the stand. On soils predisposed to podzolization, the permanent dense canopy may encourage the development of inert raw humus. Unfortunately, in the so-called "experimental method" of management, the experimentation thus far has been limited to periodic remeasurements of tree diameters and has neglected the effect of Dauerwald's pattern on microclimate and soil fertility. This is one reason why some of the German foresters claim that *méthode du contrôle* leads largely to the "control of the increment."

GLEY SOILS

Improvement and regeneration cuttings. Gley soils, with their supply of either phreatic or vadose water, usually make possible the establishment of a wide variety of species. However, these soils provide optimum growth conditions for only a restricted number of trees. The flat-rooted members of swamp forests are likely to suffer on gley soils from a lack of water resulting from lowering of the water table in periods of drought. The upland trees may be hindered in their growth by excess of water and poor aeration following melting of snow or rainy seasons. As a result, forest cover on these soils is frequently a "problem child" of forest management which requires constant care and correction.

The cutting of unwanted trees in a stand is often dangerous because of the subsequent rise of the ground water table, accumulation of superficial unabsorbed water, or "puddling," a vigorous growth of sprouts, and invasion of competing weed vegetation, particularly alder, willow, sedges, and mosses. These conditions usually dictate the use of frequent light cuts (Fig. 17–10). In young stands, improvement or sanitation cuttings should be confined to the removal of cull trees and other undesirable material. If possible, the final composition of the stand should consist of a mixture of deep-rooted deciduous species and shallow-rooted conifers, particularly spruce and fir. Such a mixture will assure freedom of the soil profile from an excess of both phreatic and vadose water.

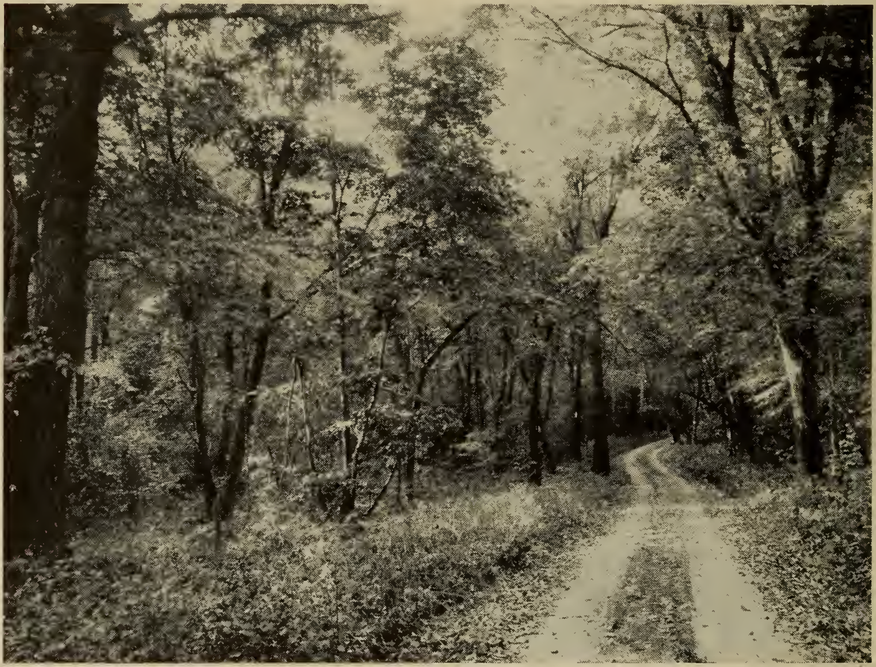


Fig. 17–10. Stand of hard maple and associated hardwoods on a gley loam soil. Natural regeneration of this forest cover by partial cuttings often presents difficulties because of a high percentage of culled and unwanted trees, rise of the ground water table, and severe competition of weed vegetation. Northern peninsula of Michigan. (U. S. Forest Service.)

The utilization and regeneration of mature stands must be conducted by careful selection cuttings with constant protection of the soil from excess water by a dense canopy providing efficient transpiration and interception of rainfall.

A considerable opening of the stand is likely to convert the areas of shallow gley soils into unproductive swamps supporting worthless shrubs, sedges, or bog moss. The more moist and cool the climate, the greater is the danger of such conversion. Hence, gley soils of the podzol region require particularly careful handling. The process of swamp formation is one of the most difficult problems in the management of northern forests, particularly those of Fenno-Scandia. A study of soils in northern Canada revealed that the development of *Sphagnum* bogs may take place after clear-cut logging on lacustrine varved clays which remain well-drained under dense stands of spruce (Wilde *et. al.*, 1954).

Although an open well cannot serve to determine the exact position of the ground water, it is a sufficiently accurate device for observation of the relative position of the water table. Therefore, well points inserted in partially cut portions of the stand and in fully stocked check plots may provide very helpful information on the results of cuttings. On fine-textured gley soils, especially on clays with unstable structure, the observation of moisture content in the surface layer may be of greater importance than recording of the ground water level. Observations of vegetation, soil conditions, and the state of phreatic or vadose water on occasional openings and windfall patches may also serve as a guide to the establishment of the proper rate of cuttings.

SWAMP SOILS

In spite of excess water, the productive capacity of organic soils varies within wide limits. Some organic deposits produce as many as 50 cords per acre of high-grade pulpwood at the age of 80 years; other peat soils are capable of supporting only scattered stands of dwarfed trees. This difference in the site quality of organic deposits has a decisive effect upon the method of silvicultural management of forest stands. The productivity rating of peat deposits is facilitated by the fact that the level of fertility of organic soils is invariably reflected in the chemical and electrochemical characteristics of ground water. Moreover, the nutrient content of various peat soils is closely correlated with the composition of their ground vegetation (Huikari, 1952). An outline of cuttings on rich brown moss peat and infertile green moss peat should suffice to illustrate the approaches toward utilization and regeneration of forest cover on swamp soils.

BROWN MOSS PEAT

Organic soils of this type are composed largely of remains of *Hypnum, Calliergon,* and *Hylocomium* mosses. They represent the early stage in the development of peat deposits and are usually confined to fertile substrata. The composition of the ground water is characterized by the presence of free oxygen, a moderately acid to slightly alkaline reaction, and specific conductance of about 0.20 mmhos.

Improvement and regeneration cuttings. The commonly practiced clear cutting of swamp forests is harmful on brown moss peat in more than one way: it lowers the inherent quality of the habitat, surrenders the area to alder and other nonmerchantable species, increases fire hazard, and eliminates from the production cycle timber stock of high growth potential. Therefore, stands on these organic soils deserve as careful a selection cutting as is being practiced on upland soils.

Stands on brown moss peat have an especially high density and an enormous capacity for natural regeneration. Therefore, even the "selection cuttings" of the lumberman's concept, extracting the bigger and better trees, could assure on these sites the steady flow of pulpwood at the rate of three-fourth cords per acre per year. The removal of crop trees can be efficiently accomplished in ten-year intervals.

GREEN MOSS PEAT

This type of peat is derived from various members of the *Sphagnum* genus and, as a rule, is characterized by an extremely low level of fertility. In part, the deficiency of nutrients is caused by their irreversible fixation in the never-decaying tissues of the bog moss. The ground water of mature deposits possesses an extremely acid reaction, negative redox potential, and a negligible specific conductance of 0.05 mmhos.

Regeneration cuttings. The average yield produced by spruce at the age of one hundred years does not exceed a dozen cords per acre on this type of organic soil. This rate of growth cannot justify the cost of intensive silvicultural management, and utilization must be accomplished by clear cutting, possibly restricted to small and dispersed areas (Fig. 17–11). This is essential because extensive cutover lands create serious danger of forest fire; they provide readily combustible material and give the wind an opportunity to attain velocity.

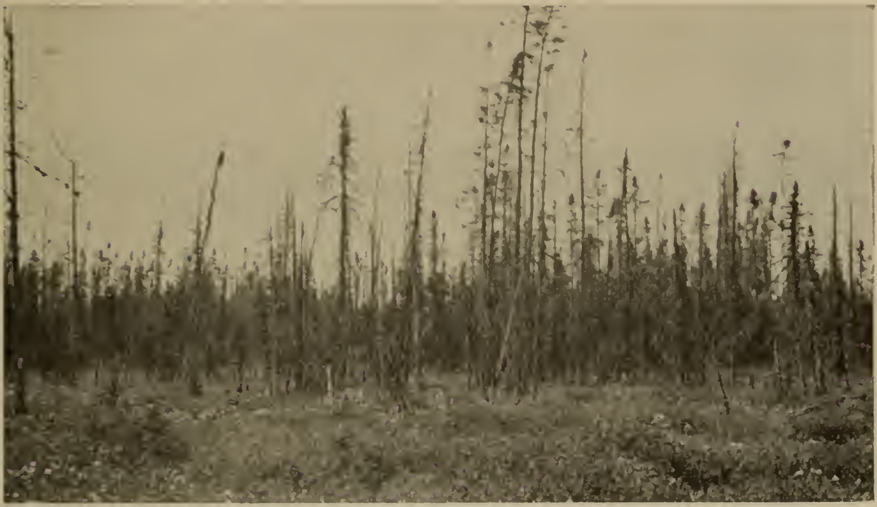


FIG. 17-11. Stand of black spruce, over 100 years old, on a stagnant moss peat bog, an example of forest cover which precludes the use of refined silvicultural techniques. Algoma region, northern Ontario.

The process of natural regeneration usually may be enhanced by leaving undisturbed groups of seed trees large enough to resist the force of wind. Leaving suppressed and otherwise inferior seed trees violates the principles of genetics and threatens to bring about progressive degeneration of growing stock.

The outlined examples feature but a few possibilities which may be encountered in silvicultural cuttings on different soils and sites. In fact, the multitude of conditions resulting from the combination of different species with soil, ground water, exposure, and geographic location does not permit prescription of silvicultural cuttings on the basis of standard formulas. With few exceptions, the cutting of each individual stand presents a problem of its own, the solution of which may be reached in part by the *savoir faire* of the supervising forester and in part by the accumulation of concrete analytical data.

If properly conducted, cuttings fully justify the claim that the axe is just as efficient a tool of reforestation as the spade or the mattock. The efficiency of this tool can be still further augmented if it is reinforced by scientific instruments recording the changes that take place in soils of partially cut stands. The binary equations of silviculture will not be solved until concrete values are substituted for one of the unknown members, the soil. Such a substitution will automatically transfer silviculture from its present questionable status of an art into the appropriate rank of science.

According to recent estimates of atomic scientists (Snell, 1955), the light of our civilization may be extinguished within another one hundred years for lack of fossil fuels. Hence, man searches for new sources of energy derived from uranium, deuterium, and direct sunlight. In these herculean labors performed for the well-being of humanity, foresters play a small but significant part. They are the technicians whose business for the last two centuries has been the conversion of the sun's energy into fuel and fuel-conserving commodities—shelter and clothing. The success of this process depends, to a great extent, upon the skill of a forest manager in exposing to the sun the maximum surface area of photosynthesizing foliage. The crux of the problem is to achieve such an exposure without deteriorating other growth conditions. Although this problem does not present a fraction of the difficulties involved in handling a controlled thermonuclear reaction, it nevertheless cannot be solved without the mobilization of all ways and means offered by science.

It would be unfair to finish this chapter without pointing out the source of the recent "revolutionary" ideas. Exactly 140 years ago, Heinrich Cotta (1816) classified silviculturists into "empiricists" and "scientists." The same author appropriately stated that, "a good forester takes a high yield from the forest without deteriorating the soil; a poor forester neither obtains high yield nor preserves soil fertility."

There can be no theory of any account unless it corroborates the theory of the earth.
—Walt Whitman, 1855.

18

Soils and forest management

Forest management is one segment of the forestry curriculum which has been long enslaved by the abstract speculations and turgid language of antiquated scholasticism. In the plain words of Roth (1925), the object of forest management is: "To build up, put in order, and keep in order forest business." As a rule, the contemporary courses on forest management endeavor to solve this problem by application of outlived "forest mathematics" in complete isolation from the physical factors of forest growth, particularly soil.

Some texts on forest management include a page or two of contemplations on the importance of soil, ecological factors, or ground-cover vegetation. However, none of these conditions is given the slightest consideration in the discussion of important aspects of forest management, namely: subdivision of forest tracts, estimates of potential productivity of managed forest lands, construction of yield tables, determination of the cut on a sustained yield basis, calculations of expected returns on reforestation investments, evaluation of forest lands, and appraisal of damages to land productivity. Despite the fact that all of these problems are organically bound to soil productive capacity, texts on forest management solve them on the basis of empirical procedures, arbitrary assumptions, and abstract formulas.

Neither farmer nor forester can efficiently regulate his crop output without managing the medium of production—the soil. In correct terms "forest management" is first of all "forest land management," the act of intelligent utilization of soil productive capacity. This chapter aims to elucidate the role which soil plays in the important aspects of forest management.

SUBDIVISION OF FOREST TRACTS FOR THE PURPOSE OF MANAGEMENT

As stressed in the discussion of soil survey, the first, all-important step toward organized timber production is an inventory of land areas of different productive potentials. Such an inventory must give primary attention to the suitability of the land to support different tree species, actual or potential rate of growth of forest stands, desirable lengths of rotation, and feasibility of natural or artificial forest regeneration by different silvicultural methods. It is obvious that all of these aspects of forest growth are intimately correlated with the nature of soils and, in hilly or mountainous topography, with exposure and gradient. Therefore, utmost effort should be made to subdivide a managed forest into compartments that have uniform physiographic or ecological conditions (Wilde and Scholz, 1930).

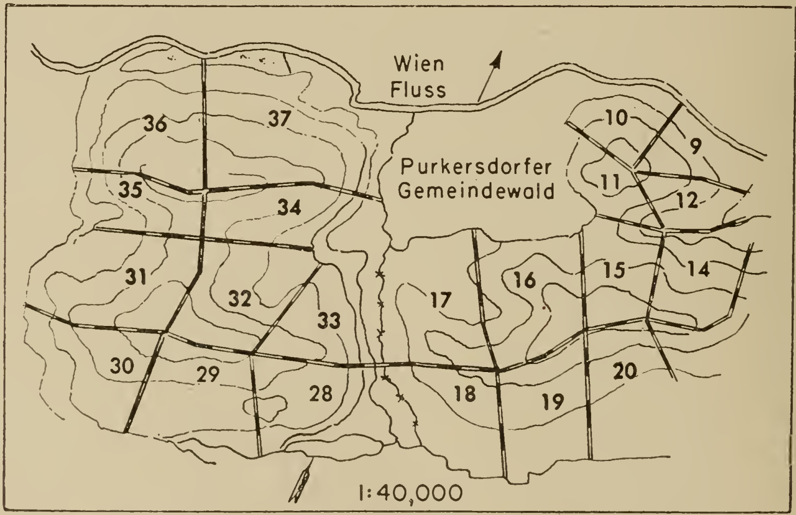


Fig. 18-1. Subdivision of the Purkersdorf Forest near Vienna according to the traditional approach. Note the disregard of the ecological aspects of topography and the diversity of site conditions within individual compartments.

Figure 18–1 gives an example of an old-fashioned subdivision of a forest tract that completely ignores the conditions of forest growth and requirements of efficient silvicultural management within the individual compartments. Thus, compartment 37 embraces three totally incompatible sites—eroded hilltop, fertile slope, and floodplain in part occupied by marsh.

SITE QUALITY OF FOREST LANDS AND FOREST STANDS

In the descriptive language of Davis (1954), "growth is the life blood" and "a sustained flow of harvest products is the heart of forest management." In the same anatomical terminology, the site quality is the backbone of all transactions of forestry enterprise; the most important of these is the rational exploitation of forest products without depletion of available wood capital. The site quality determines the volume as well as the value of produced timber. Therefore, the site quality regulates the intensity of forest management, for a large expense on stand improvements is usually feasible only on tracts of high productive potential.

"Site quality" of silviculturists is essentially synonymous with "productivity rating" of agronomists. Both terms aim to express how good the land is and how much corn, timber, or other crops it can produce. However, in farming, with its short rotations, the term "productivity rating" refers to the **potential site quality** of the land, determined largely by the **primary** or **physiographic growth factors.** These factors comprise general climatic conditions, topography, drainage, geologic origin of the soil, supply of nutrient-bearing minerals, soil texture, the makeup of the soil profile, and other features that can be appraised by analytical methods and recorded in soil survey.

In forestry the simple concept of "productivity rating" is complicated by the greatly extended period of crop production and subsequent modification of environment by the growing stock. When a forest stand closes its canopy, the productive capacity of the soil is appreciably modified by the influence of subfoliar microclimate and many **secondary** or **biogenic growth factors**, such as forest litter and symbiotic organisms. Moreover, the site quality of forest lands fluctuates within wide limits, depending upon the variation in the rate of growth exhibited by different tree species on the same soil.

As a general rule, foresters determine the site quality by measuring the rate of growth of trees that happen to occupy the forest tract at the time. Because there is a close correlation between the height growth and the yield of forest stands, sites are usually classified on the basis of the average height of the dominant trees at a certain age, such as 50 or 100 years. Thus, a fast-growing stand of white pine, characterized by an average height of 70 feet at 50 years, is referred to as a stand of site index 70. The approximate yields of fully stocked stands of this site index would range from 3,000 cubic feet at 30 years to 14,000 cubic feet per acre at 100 years.

The site quality established by analysis of existing forest cover, or the immediate site quality of a stand, is an important but not all-inclusive criterion of soil productive capacity. Thousands of acres of excellent pine lands in central Europe were reforested to spruce. As a consequence, adjacent tracts of outwash sands exhibited "very good" site quality under Scotch pine and "poor" or "very poor" under Norway spruce (Wilde, 1930). This discrepancy results from the inherent moisture and nutrient requirements of the two species, as well as from their capacity to intercept different quantities of light and precipitation and to produce litter of different quality (Wittich, 1948). Soils of glacial deposits in the United States, which produce more than a cord per acre per year under plantations of red pine, are at present largely occupied by post-fire stands of scrub oak yielding only ¹⁄₁₀ cord per acre per year. These examples suffice to illustrate the importance of the two basic concepts that must be considered in forest management: productive capacity of the growing stock or the **actual site quality** and productive capacity of the land or the **potential site quality.**

A prerequisite for the determination of the potential site quality is a careful soil survey delineating the lands of different adaptation and productivity ratings. In the course of the survey an estimate is made of the tree species which are best suited to different soil types, considering the ecological and economic aspects. Then statistically significant site indexes for these species on given soil types are determined by mensuration analyses of representative stands found on the forest property or in neighboring territory. This information, in conjunction with suitable yield tables, provides a reliable basis for a solution of several vital problems of forest management, such as the establishment of rotation, determination of the annual cut on a sustained yield basis, estimates of the financial soundness of investment on reforestation, and evaluation of forest property.

PREPARATION OF YIELD TABLES

Yield tables give the volume of the timber per acre in cubic or board feet, at various ages of the stand, usually at ten-year intervals (Fig. 18–2). Yield tables also often include information on the total

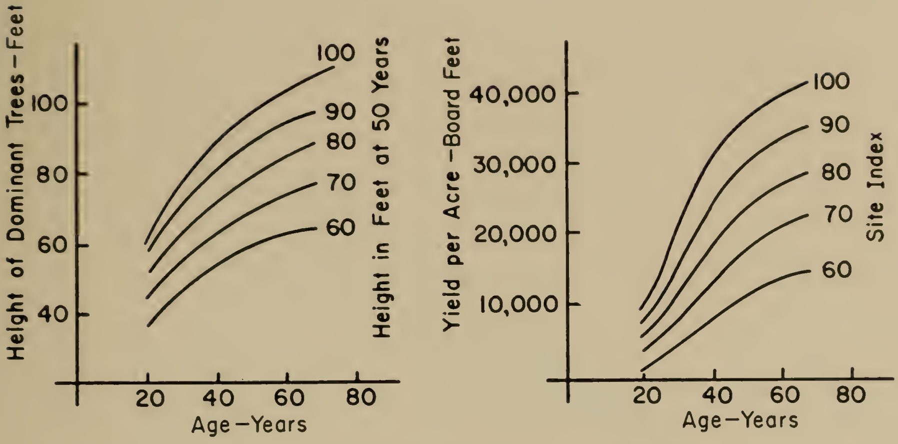


FIG. 18–2. Site index curves and normal yield tables for slash pine. (Adopted from Miscellaneous Publication No. 50, USDA, 1929.)

number of trees, basal area, average diameter, average height of the stand, and other data indispensable in efficient forest management.

With the aid of yield tables, the volumes of growing stands are estimated by determining the age of the stand and average height of the dominant and codominant trees on representative sample plots. The site index of the stand is found by referring to the site index graph, exemplified by Figure 18–3. The yields for this site index are then interpolated from the yield table.

Because the volumes of timber given in yield tables correspond to fully stocked stands, the volumes of understocked stands are computed by multiplying the normal volume by a reduction factor. The reduction factor is determined either by ocular estimate or by measurement of the basal area of the stand. The measurements are usually confined to sample plots.

In many instances it is possible to utilize available yield tables after testing their applicability by mensuration analyses of stands on typical sites. If the actual volumes of timber do not match closely with those given in the available yield tables, sometimes it is possible to make suitable interpolation on the basis of stem analyses. Otherwise, it is necessary to construct local yield tables, a task which is often unavoidable in intensive management on a sustained yield basis as well as in management of uneven-aged and mixed stands.

It has been a common practice in the past to construct yield tables by determining the rate of growth of stands on the most productive and on the least productive sites by actual measurement of timber. The yields thus determined are related to age and expressed as

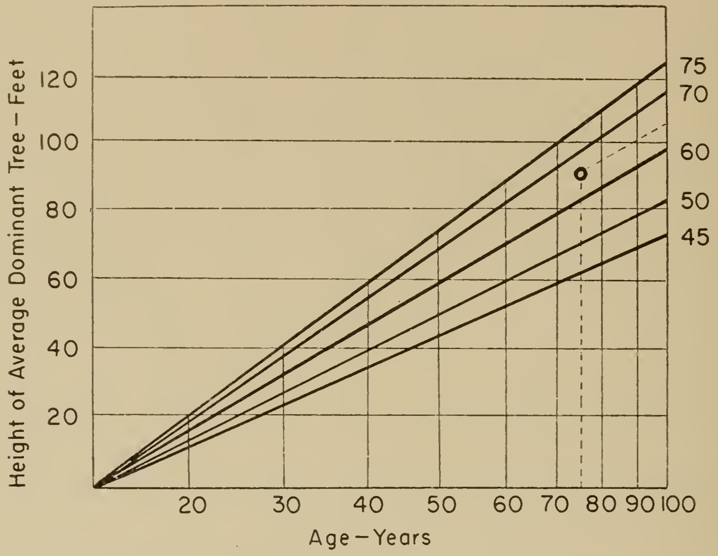


FIG. 18–3. Site index graph for second-growth white pine. If the average height of dominant trees is 90 feet at the age of 75 years, the site index of the stand is 65. (After Gevorkiantz and Zon, 1930.)

curves. The yields of timber for intermediate sites are then established by drawing additional curves equally spaced between those for maximum and minimum rates of growth. As recent investigations have shown, however, the actual production of wood on different sites does not correspond to these artificial standards established by interpolation. Consequently, the general tendency of modern practice is to determine the actual rate of growth of stands on land types characterized by definite altitude, topographic position, soil profile, ground water level, or outstanding floristic features. Figure 18–4 gives an example of a yield table for Norway spruce in the region of Austrian mountains. Figure 18–5 presents the site index graph and the yield table for Scotch pine on several floristic sites of Finland.

Under some conditions, the rate of growth of stands on different soils is expressed by curves that have very dissimilar trends. For example, in a continental climate, stands of aspen on upland sandy soils show a very rapid initial growth which sharply declines at the age of about 30 years because of the limited supply of soil water. On the other hand, the growth of aspen on soils underlain by a high water table is first depressed by an excess of moisture and insufficient aeration but gradually improves after the intercepting and transpirational effects of the stand's canopy have lowered the ground water table. Other modifications in the rate of tree growth that take place

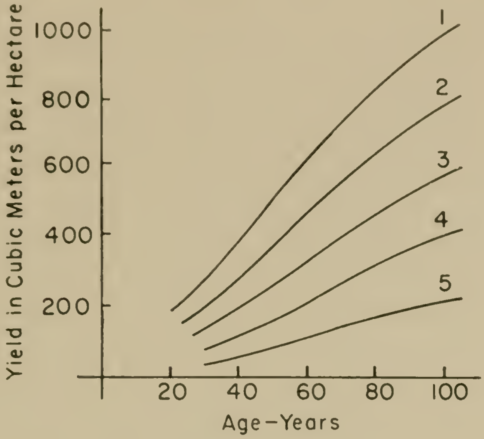


Fig. 18-4. Yield table for Norway spruce of mountain regions. Site 1 (excellent): deep humus loams at altitudes less than 1000 meters. Site 2 (good): sandy loams underlain by sandstones or schists at elevations less than 1200 meters. Site 3 (fair): shallow sandy loams on schists and shallow humus soils on limestone at elevations from 1000 to 1400 meters. Site 4 (poor): shallow stony or wet soils from 1400 to 1600 meters. Site 5 (very poor): exposed areas of high altitudes above 1600 meters. (After A. v. Guttenberg.)

in the course of stand development were stressed by Heiberg and White (1956).

These examples should suffice to disclose the possibility of gross errors involved in the construction of yield tables without due consideration of the nature of habitat, particularly soil.

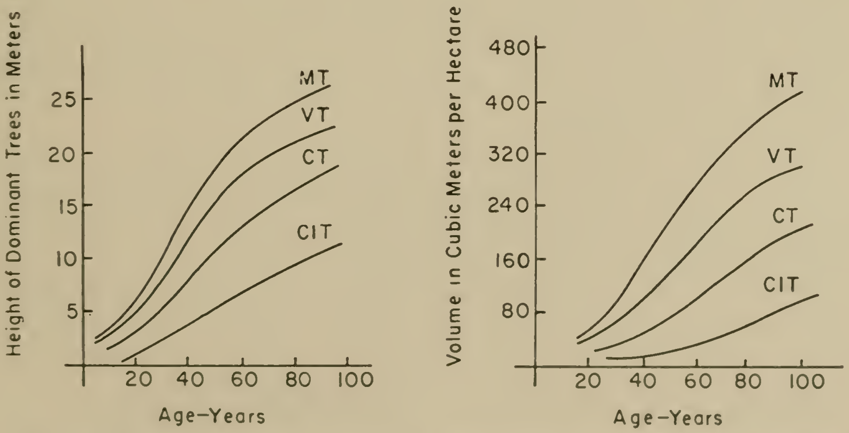


Fig. 18-5. Height growth and yields of Scotch pine on different floristic sites of Finland: *ClT–Cladonia* site; *CT–Calluna* site; *VT–Vaccinium* site; *MT–Myrtillus* site. (Adopted from Ilvessalo, 1923.)

DETERMINATION OF THE ANNUAL CUT

A supply of standing timber represents a capital which provides a steady income in the form of annual increment. Therefore, standing timber is often compared with a capital deposited in a bank and paying dividends at a certain rate of interest. This analogy holds true only in some instances and may be totally misleading. The dividends left in the bank bring additional income according to the law of compound interest; the increment of wood not removed from the growing stock of the maximum productive capacity is automatically annihilated by the deterioration of overmature timber. Consequently, the all-important problem of forest management is the maintenance of the so-called "normal volume" of growing stock which provides the maximum periodic income. In broad terms, this normal volume is equal to one-half the supply of timber of fully stocked stands at their maturity.

In order to bring the managed forest to the "normal" state of maximum productive efficiency, the exploitation of the forest must proceed for a certain period at either a reduced or an accelerated rate determined by the volume of timber removed in annual cuts.

There are many approaches toward the determination of the annual cut under sustained yield management. Among them the use of the "exploitation quotient" is the least elaborate procedure suggested by Hundeshagen (1826). According to this method, the annual cut is determined on the basis of the formula:

$$AC = \frac{NI}{NV} \cdot AV$$

where AC is annual cut, NI is normal or maximum increment of the entire management unit, NV is normal volume of timber, and AV is actual volume of timber.

Accordingly, the annual cut on a forest tract of 10,000 acres that supports a total volume of 120,000 Mbf and has the normal volume and increment of 200,000 and 5000 Mbf, respectively, would be: $5000 \div 200{,}000 \times 120{,}000$ or 3000 Mbf.

It is obvious that when the undercutting or overcutting brings the actual volume to the level of the normal volume, the exploitation quotient will become identical with the normal or the maximum increment of the forest estate under the management.

The actual volume of timber is determined by cruising, whereas the normal volume and the normal increment are estimated for fully stocked stands from the yield tables on the basis of corresponding site qualities.

This and similar methods of determination of the annual cut provide satisfactory results in management of well-stocked forests whose supply of mature timber exceeds that of the most efficient normal growing stock. However, if the managed forest unit includes extensive cut-over lands to be reforested and areas supporting young stands, the calculation of the normal volume and increment on the basis of previous records or arbitrarily established figures becomes highly speculative. Under such conditions the determination of the annual cut must be based on a careful soil survey and subsequent estimate of the site quality of cut-over and recently reforested areas. Following this, the expected rate of growth of stands and the yields produced at the end of rotation can be established from suitable yield tables. Only such a procedure permits a reasonably accurate estimate of the most efficient annual cut that will lead to the maximum income from the managed forest unit.

ESTIMATE OF THE RETURN ON REFORESTATION AND LAND IMPROVEMENTS

Before planting an area to a certain tree species, it is advisable to ascertain the expenses involved, the yields that may be produced at different ages of the plantation, and the expected return on the investment. The expenses include the value of land (L), cost of planting (C), and carrying charges (e), including cost of protection, silvicultural care, and taxes. The total cost with the compound interest on the capital invested at an accepted rate of interest (p) up to the age when the plantation becomes merchantable (n) is then compared with the stumpage value of the plantation (V) as inferred from yield tables and estimated market prices according to the following formula:

$$V = L(1.0p^n - 1) + C \cdot 1.0p^n + \frac{e(1.0p^n - 1)}{0.0p}$$

Suppose the value of the land is \$4.00 per acre, the cost of tree planting \$20.00, carrying charges \$0.50, and the rotation period 40 years. The minimum stumpage cost at the end of the rotation, considering a 4 per cent interest rate, would be:

$$V = \$4.00(1.04^{40} - 1) + \$20.00 \cdot 1.04^{40} + \frac{\$.50(1.04^{40} - 1)}{0.04}$$

$$= \$15.20 + \$96.00 + \$47.50, \text{ or approximately } \$160.00 \text{ per acre.}$$

Calculations of this kind deserve consideration only when they are supported by data of suitable yield tables and a careful survey of the land proposed for reforestation, that is, information that permits a reasonably accurate estimate of the yields produced at the end of rotation. A concrete example from contemporary practice should help to outline financial possibilities encountered under different conditions.

Let us assume that the calculated stumpage cost is applicable to podzolic sandy soil of granitic outwash to be reforested to red pine. According to available information, soils of this type have a potential site index for red pine of about 70 and produce 35 cords per acre at 40 years. Consequently, the expected stumpage cost of a cord will be \$160.00 ÷ 35 or \$4.57, which figure is low enough to promise a reasonable profit. If, however, the same soil is planted to white spruce, producing 16 cords at 40 years, the maximum stumpage cost of \$10.00 per cord indicates a possibility of losing money on the investment.

With slight modifications the same technique could be applied to investments other than reforestation, for example improvement cuttings, drainage, and application of fertilizers. However, it must be borne in mind that calculations on the basis of present cost of wood are only approximate. Even during a brief period of 20 years the stumpage price of wood may be greatly altered by the change in the purchasing value of currency as well as the technique of wood utilization, transportation facilities, and conditions of the domestic and international wood market.

EVALUATION OF LAND

In some instances the value of forest land (L) is estimated by the capitalization of a permanent periodic income resulting from the net profit cleared after the sale of timber crops (Y):

$$L = \frac{Y}{1.0p^n - 1}$$

Hence, if the value of timber at 40 years is \$80.00 per acre and total expenses for the period at compound interest of 4 per cent are \$60.00, the net income is \$20.00 per acre and the value of the land is:

$$L = \frac{\$20.00}{1.04^{40} - 1} = \$5.20 \text{ per acre}$$

If the area to be appraised is cut-over land, the evaluation is made by highly speculative estimates of the expected yield of timber, inferred from the yield tables for the species best suited to the land, and probable expenses on the establishment and raising the stand.

The results of these and similar calculations may give some idea of land value from a forestry viewpoint and may be of significance in the exchange of lands; they may serve as a theoretical basis in land acquisition or taxation (Wilde, 1930). However, the actual value of land is influenced by a number of factors other than soil productivity and the expected price of stumpage. Among these factors the following are of importance: danger of fire and extent of the existing fire protection measures; danger of injury by climatic factors, insects, and fungi; stability of the local wood-using industries; individual interest of the purchaser; and especially the distance from the market and passability of roads. Because of this, the practice of land evaluation usually follows a pattern which is divorced from abstract calculations.

As a rule, a necessary prerequisite to land appraisal is a detailed soil survey which takes into consideration topography, morphology of the soil profile, position of the ground water table, soil texture, content of organic matter, and other factors important in timber production. Particular attention is given to tracts depleted by fire, cultivation, or grazing (Aaltonen, 1937; Süchting, 1939).

APPRAISAL OF DAMAGES TO THE PRODUCTIVITY OF FOREST LAND

Forest soils as well as forest stands may be damaged by a number of adverse conditions such as forest fire, damming of streams, drainage, disposal of waste products, toxic industrial fumes, and grazing. Where it can be shown that a certain person or a corporation is responsible for the alteration of conditions, the owner of the damaged forest tract is entitled to a fair remuneration.

The appraisal of damage to the growing stock is made according to established principles of forest finance. The remuneration for the destruction of a mature stand amounts to the stumpage value of the destroyed timber. In the case of nonmerchantable reproduction or plantations, the allowable damages consist of the cost of planting or reforestation plus the compound interest on this investment computed from the time of initiation of the stand to the time of destruction.

In order to establish a basis for the evaluation of damages to the productivity of the soil which will hold in a court of law, the claims should be supported by soil analyses and competent profile descriptions of both damaged and normal soils. The damage must also be substantiated by evidence based on mensuration studies from adjacent localities or on data from authoritative literature. If yield tables are available, they may be used to express in concrete form the decrease in production due to soil deterioration.

The extent of the damage is usually established empirically on the basis of current prices of the normal and deteriorated soil. Otherwise, the amount of remuneration (D) is calculated as the difference between the discounted stumpage price of the expected yields of timber for the original site (V) and the deteriorated site (V_1):

$$D = \frac{V}{1.0p^n - 1} - \frac{V_1}{1.0p^n - 1}$$

This calculation assumes that the species present are those most suitable to the soil and are at the age of maximum merchantability. Ordinarily, the cost of planting and the carrying charges are the same on normal and damaged sites; hence, the two values cancel out. This approach is illustrated by the following concrete example.

A well-drained mull loam supported a white pine stand of site index 70 capable of producing 63 Mbf per acre at 70 years (International log rule). Due to the erection of a dam and subsequent change in the ground water level, this soil has deteriorated to a gley loam capable of supporting a white pine stand of site index 60, with a potential yield of 52 Mbf at the same age. If the local stumpage value is \$20.00 per Mbf and the accepted interest rate 4 per cent, the damages are:

$$D = \frac{63 \times 20.00}{1.04^{70} - 1} - \frac{52 \times 20.00}{1.04^{70} - 1} = \$86.94 - \$71.76 = \$15.18 \text{ per acre}$$

If the cost of planting is higher on the damaged site, additional claims may be made.

Considering the cost of the legal procedure, a lawsuit for remuneration of damages inflicted on land productivity would be justified only when the damaged land has a high value or when a large acreage is involved.

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